Photovoltaics in the built environment:

an application for Malaysia

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Abstract

The applications of photovoltaics (PV) in the built environment has been popularly termed as Building integrated PhotoVoltaics (BiPV). The PV modules form part of the building and generate electrical power. A number of working BiPV programmes can be seen in several countries, but its application in the sunnier climate developing nations in the lower latitudes has been lacking, despite having numerous stand-alone PV systems. In Malaysia, PV technology has been established for remote power systems in an apparently increasing demand. However, BiPV technology application is absent, despite increasing trends in energy needs generally. The purpose of this project was then to explore the applicability of BiPV technology in Malaysia via computer modelling, with a synergistic advantage of introducing it into the country. The study involved work on an experimental set-up at the Whittle Hill Farm (WHF) office building, in the UK, which has a 2.64 kW peak (kWp) grid-interactive BiPV installation. A computerised monitoring system was installed with the micro-climate and PV performance data compiled and analysed. These data were then used in a comparative study against a selected, commercial BiPV computer model, PVSYST 2.0. Despite inherent design and operating difficulties of the WHF installation, results of the study have been encouraging. Further work involved an exploratory BiPV simulation for the Standard Malaysian School Building (SMSB) design. These simulations were undertaken within limits of the SMSB design and architectural constraints using PVSYST 2.0, enhanced with a thermal computer model SUNREL 1.0β. Analyses of the simulated results for electrical power generation using a combination of design parameters revealed that the BiPV-SMSB system to be very promising. However, technical issues regarding array temperatures needed design attention, and cost-effectiveness of such applications was still an issue to be reckoned with. A methodological guideline for the application of BiPV technology in the Malaysian built environment has been proposed. It was generally concluded that BiPV application in Malaysia seemed favourable and a demonstration installation has been recommended.

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I declare that the content of the submission represents solely my own work. The contents of the work have not been submitted for any other academic or professional awards. I acknowledge that the thesis is submitted on the conditions in the Regulations. I declare that the work was carried out as part of the course study for which I was registered and not previously or subsequently; and I draw attention to any relevant considerations of rights of third parties or of security which might merit a restriction on loan or access.

Sulaiman Shaari, June 1998.

Contents

Nomenclature

Symbol	Units	Meaning
-	kWh	energy unit
-	$kWhd^{-1}$	energy per day
-	$kWhm^{-2}$	energy density per unit area
-	kWp	peak capacity rating of PV array
-	$kWhd^{-1}kWp^{-1}$	an index, energy per day per installed peak capacity of PV power
Id	A	diode current
I_L	A	diode photocurrent
Imp	A	maximum power point current
Io	A	diode reverse current
Isc	A	short circuit current
Ish	A	shunt current
P	W	electrical power
Pmp	W	maximum power point
PR	%	Performance Ratio
BiPV	-	acronym for Building integrated PhotoVoltaics
R	Ω	electrical resistance
R_L	Ω	external electrical load
Rsh	Ω	shunt resistance
Rs	Ω	series resistance
T	°C	temperature
V	V	voltage
Vmp	V	maximum power point voltage
Voc	V	open circuit voltage
q	C	electronic charge
qV	eV	electron volt
h	Js	Planck's constant = 6.63×10^{-34}
k	$Wm^{-2}K^{-4}$	Boltzmann constant = 5.67×10^{-8}
A	-	ideality factor, a curve fitting parameter

Chapter 1. Introduction

1.1 Background to the research

Terrestrial PhotoVoltaic (PV) power has been traditionally popular for remote power systems and still are being used widely in areas where connection to the national grid is either economically prohibitive or plain impossible. These areas are often sparsely populated with lower energy density requirements. Only after years of experience with these isolated PV power systems and the fast paced advancements in power electronics, the idea of using PV power systems in the more densely populated urban areas was instigated. In response to this, the concept of grid-connected and grid-interactive Building integrated PhotoVoltaics (BiPV) was concocted, in which the PV modules make up part of the building envelope itself. Today, in the Northern American continent, Japan and several European nations, BiPV technology can be seen working in many demonstration projects. Of late, initial large-scale implementing stages of BiPV grid-connected and grid-interactive systems have been started, especially in urban areas of these nations. This is seen as moving in a positive direction towards using energy sources that are benign to the environment, in response to the global climate change pressures.

Whilst momentum is being gained in BiPV grid-interactive applications in the developed nations, about half of the world capacity of PV technology have already been established in the developing nations as traditional isolated power systems. It seems as just a matter of time when BiPV grid-interactive systems would make its way into the lives of the people in these developing nations, of which Malaysia is a part of. It can be seen that while PV technology in Malaysia has been established, its applications to date have been solely for remote power systems, despite apparently increasing demands in electrical power with an expanding market for PV applications. With a large number of rooftops already available in Malaysia, an exploratory study on the application of BiPV grid-connected systems in the country has been proposed, via computer modelling, in this research study.

1.2 Objectives

The main objectives of this research project are to:

- Acquire updated developments of BiPV applications through studies of the literature.
- Gain practical foundation experience and appreciation of the technology through the monitoring of a real BiPV installation in the UK.
- Achieve confidence levels of the theoretical and practical capabilities of a selected commercial BiPV computer model.
- Extend and contribute to knowledge by executing the selected computer model to a new exploratory situation for BiPV application in the Malaysian built environment.

The final aim of this research project is to explore the applicability of BiPV technology in the standard Malaysian school building design. A synergistic advantage of this project would be to introduce the technology into the Malaysian built environment generally. It is hoped that the outcome of this project is seen as an innovative augmenting alternative to Malaysia's power needs via the built environment, as well as involving her future generation right from an early age.

1.3 Scope of the research

This project has been formulated to comprise of a theoretical and practical phases. Initial stages of the research covered background literature surveys on the developments of BiPV applications and modes of integration in several existing countries. An overview of the Malaysian literature on energy scenario was also included with emphasis on PV applications and certain related literature. A presentation of the basic physical properties of PV operation was also discussed.

The practical phase was formulated in the research project to provide foundation and appreciation of a real BiPV installation. It was planned that experience from the experimentation of such a practical installation would provide valuable foundation into BiPV technology concerning issues and problems relating to the monitoring and installation of such systems. This was achieved by setting up a computerised stand-alone monitoring system at the Whittle Hill Farm (WHF) office building, a 2.64 kW peak capacity (kWp) grid-interactive BiPV installation in Leicestershire. Analytical work on the data to obtain general indices of performances of the unique WHF installation was done and compared to several other existing sites.

The next part of the project involved the theoretical phase. Initially, a selection of dedicated commercial BiPV computer models were surveyed based on selected criteria. Upon satisfactory reviews, the BiPV computer model PVSYST 2.0 was chosen. The next stage involved modelling work of the grid-interactive BiPV-WHF system using PVSYST 2.0. It involved the setting up of the BiPV-WHF system installation and generating simulated results which were then compared to the measured values. Confidence levels of the predictions against the measured values were obtained and disparities between them were analysed and discussed. Proposals for enhancements of the model were then made in view of its further use in the Malaysian simulation executions.

In the final part of the research, further simulation work for a new application in the Standard Malaysian School Building (SMSB) design were made. This was possible as PVSYST 2.0 proved to have the flexibility to model complex applications in new situations and different climates. The BiPV-SMSB simulations for Malaysia were done with regards to the electrical power generation using PVSYST 2.0 and enhanced with a thermal computer model SUNREL 1.0β. Combinations to obtain the optimum BiPV outputs within the architectural constraints of the SMSB design were explored and issues relating to the system performances were identified. As a direct consequence of the design considerations to achieve optimum BiPV performance in the SMSB design, air temperature predictions in the SMSB classroom have also been obtained. Finally, a methodological guideline for the applications of BiPV technology in the Malaysian built environment was formulated as a direct outcome of the research project. Conclusions were drawn with regards to the prospects of the applicability of BiPV technology in Malaysia and recommendations for further research were also suggested.

1.3 Outcome of research

The main outcome of this research project is in the form of a scientific and educated knowledge of the applicability of BiPV technology in the SMSB design specifically, and the Malaysian built environment generally. This has been achieved and is presented in the form of a methodological guideline for its application in the Malaysian built environment. It is meant to be used as a fast and easy reference for prospective practical work relating to BiPV applications by architects, engineers, designers and as many possible users in the built environment in Malaysia.

Chapter 2. Overview of Photovoltaics and its Integration in the Built Environment

2.1 Overview of photovoltaics

Photovoltaics (PV) is a phenomena where electricity is produced from the illumination of light on certain semiconductor materials. Its discovery dated back to the early findings by Edmond Becquerel in 1839 in the form of a wet cell. The first report of PV phenomena in a solid selenium was published in 1877 at Cambridge and the first practical PV cells were developed at the Bell Laboratory in the 1950's. Much research and development have been made since then until its real impact felt in extra-terrestrial applications in the 1950's. From a humble 5 milli-Watt peak (mWp) first application on the Vanguard spacecraft in 1958, the first PV power station was finally built in Hysperia, California at 1 Mega-Watt peak (MWp) in 1982. Today, the largest PV power plant in the world is the Carissa Plains PV power facility, rated at 5 MWp, situated in California, USA. PV power can now be seen in use in world-wide terrestrial remote telecommunications, isolated localised power systems, medium scale central power systems as well as grid-connected and grid-interactive systems in buildings (NREL, 1998; EREN-DOE, 1998; FSEC, 1998; Sheppard and Richards, 1998; Hestness and Andersen, 1997; Watt *et.al.*, 1997a; McNelis *et.al.*, 1996; Sick and Erge, 1996; EUDG XVII, 1995; PViB Pack, 1995; Markvart, 1994; Humm and Toggweiler, 1993; Roberts, 1993; Strong and Scheller, 1993; Derrick, 1993; Duffie and Beckman, 1991; Odukwe and Mudhopadhyay, 1986; James, 1986; Adanu, 1986; Riddoch and Wilson, 1981). Its advantages include reliability, no moving parts, cheap operation and maintenance, silent, creates no atmospheric pollution while in operation, modular and can be quickly installed.

2.1.1 Global market trends

The commercial market of PV production was estimated to be at 5 MWp in 1981 and at 60.1 MWp in 1992 (Derrick, 1993), at 62 MWp in 1993 and up to 83 MWp in 1995 (DeLaquil III, 1996). The bulk of the shipment has been dominated by crystalline Silicon modules which makes up between 77 to 90 % of the total volume (Barnes, 1997; PVPOWER, 1997; DeLaquil III, 1996). Another estimation of the world shipment of PV modules was at 74 MWp in 1996 and has been projected to reach up to 1200 MWp by 2010 and 9000 MWp by 2020 (McNelis *et.al.*, 1996). European PV shipment amounted to 17 MWp in 1992 (EUDG XVII, 1995). Other publications cited the market production size at 70 MWp in 1995 and projected the market production size at 300 MWp just after the year 2000 (PViB Pack, 1995). Projections of the total market production size for PV by the year 2000 ranged from 250 MWp to 1000 MWp at a 20 % growth rate (Hill, 1993) or 700 MWp by the year 2000 (Prince, 1990). Another projection estimated the PV production to be approximately 140 MWp with 550 MWp installed capacity by the year 2000 (Barnes, 1997). A separate estimate stated that the current total world PV installations was around 580 MWp (Watt *et.al.*, 1997a). The use of PV technology in the developing nations was projected to reach 40 % of the total world share in 2020 (Darkazalli and Nowlan, 1996).

Some of the major industrialised countries involved in the production of PV modules are: France (NAPS, Photowatt), Germany (DASA, Siemens), Italy (Helios), Japan (Kyocera, Sanyo, Sharp), Netherlands (RES, Shell), Spain (Isophoton), UK (BP Solar) and USA (Amoco, Solarex). Some of the developing countries involved in the production of PV modules are: India at 9.0 MWp, China at 5.5 MWp, Saudi Arabia at 1.5 MWp, Singapore at 1.5 MWp, South Africa at 1.5 MWp, Algeria at 1.0 MWp, Brazil at 1.0 MWp, Korea at 1.0 MWp, Oman at 1.0 MWp, Egypt at 0.5 MWp, Thailand at 0.2 MWp, Argentina at 0.1 MWp and Indonesia at 0.1 MWp (Darkazalli and Nowlan, 1996). This gives a total of 25.9 MWp capacity manufactured by the developing countries. The major scenario of PV market share is depicted in Figures 2.1 and 2.2:

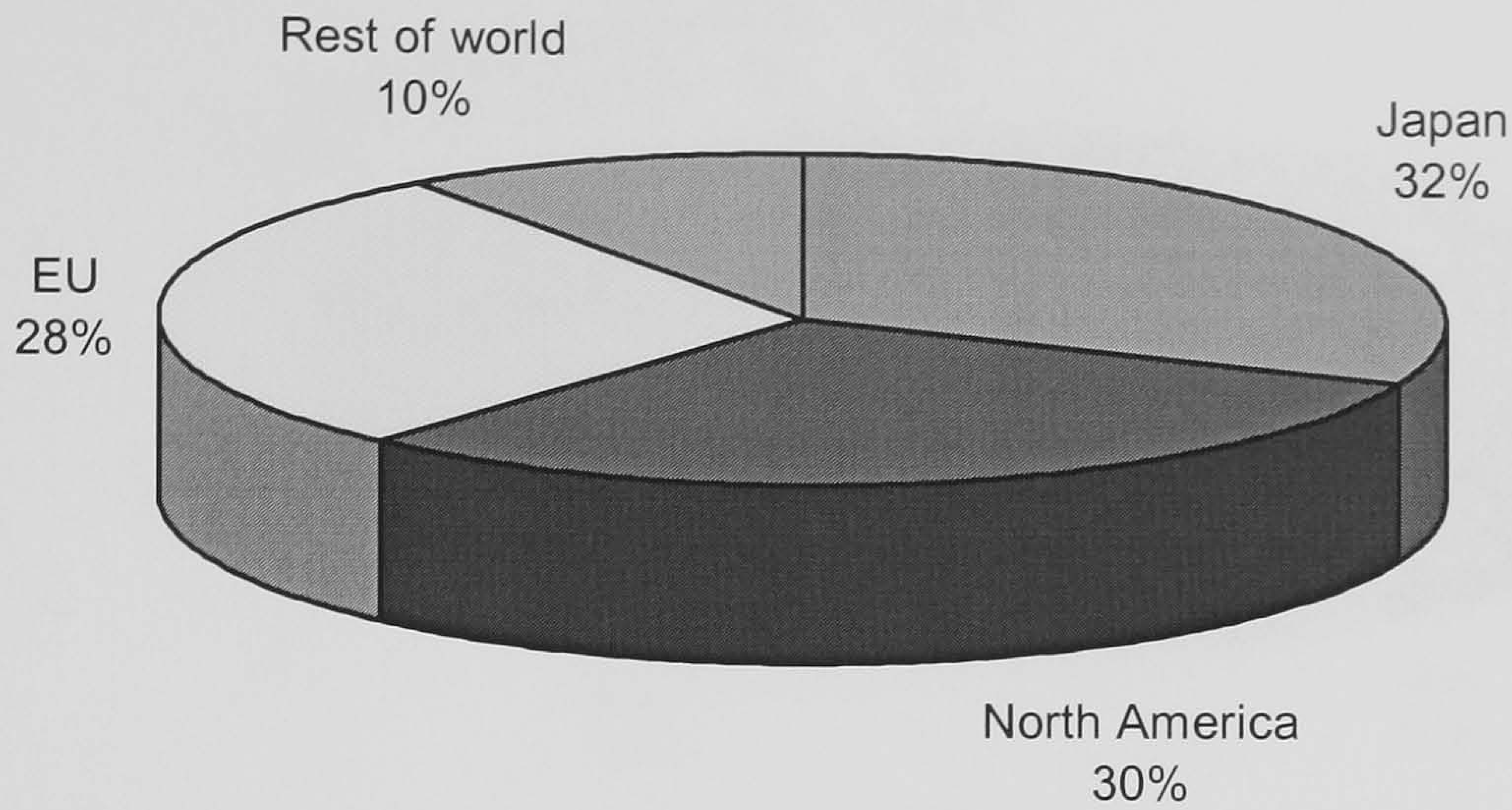


Figure 2.1: Major producers of PV modules with a production of 60.1 MWp (Derrick, 1993).

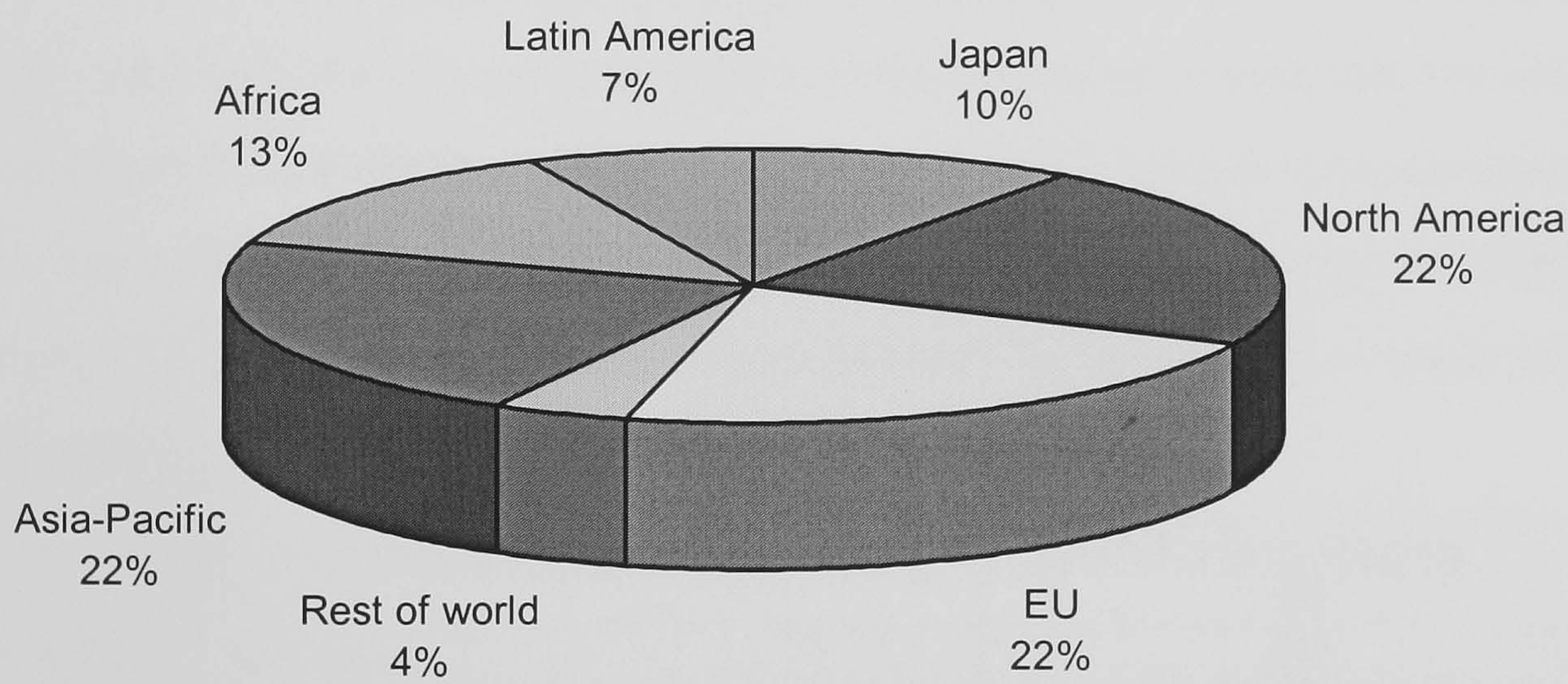


Figure 2.2: Major end-users of PV technology with a production of 60.1 MWp p.a. (Derrick, 1993). The developing nations make up about 46 % of the total number of end-users.

Figures 2.1 and 2.2 show the estimated PV modules production and their end-users by region. They show that whilst the regions of North America, Japan and the EU produce about 90 % of the world PV modules, 46 % of these modules end up being used in the developing nations of the world. The installed capacity within member countries of the International Energy Agency (IEA) was 53.5 MWp in 1990 and raised to 175.7 MWp in 1995 with an average growth of about 27 % p.a. (Barnes, 1997). The total value of business as reported in 1995 was about US$ 719 million (PVPOWER, 1997). The percentage breakdown by country in the IEA is shown in Figure 2.3:

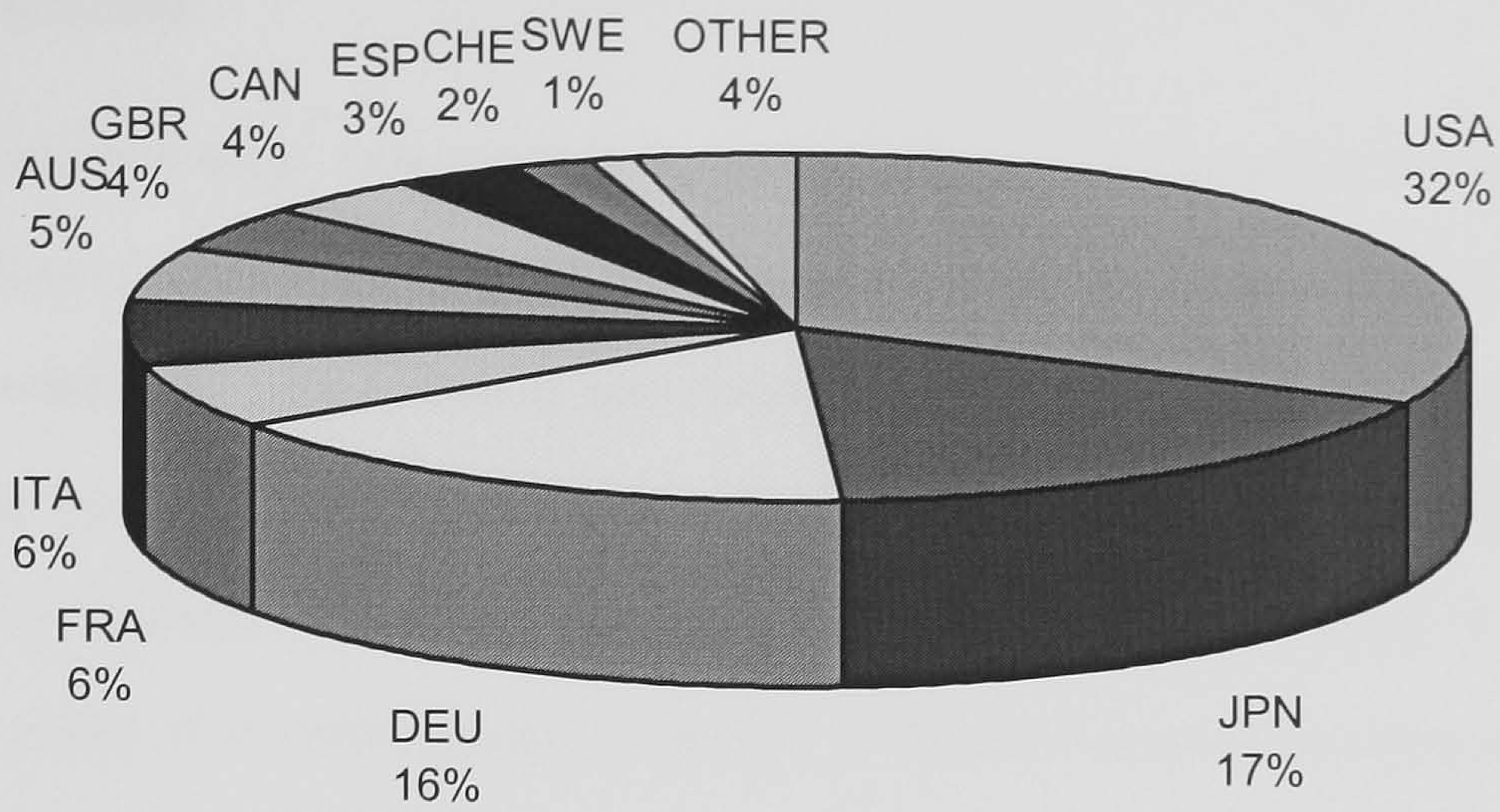


Figure 2.3: Value of business amongst IEA member countries in 1995 with a total of US$ 719 million (PVPOWER, 1997). The UK has a 4 % market share.

Figure 2.3 shows the percentage of PV business estimation for the IEA member countries. The USA, Japan and Germany control about 65 % of the total market of about US$ 719 million. A major impediment to the proliferated use of PV technology has been the cost of the modules themselves. The production of the modules consumes large amounts of energy, making them highly expensive (Green, 1982). The typical production energy and costs for crystalline PV modules with a module efficiency of 12.5 % are shown in Tables 2.1 and 2.2 respectively:

Basic production process	Specific energy ($kWhkg^{-1}$)
Sanding	24
Purification	621
Conversion	1700

Table 2.1: Energy consumed for production of a silicon solar cell (Green, 1982).

Production stages	Cost (US$ per m^2)
Wafer production	-
- material	50
- casting ingot	50
- sawing wafer	100
Cell fabrication	100
Lamination	100
Module assembly	100
Total	500

Table 2.2 Typical production costs (Kelly, 1993).

2.1.2 Efficiencies

Efficiency records of solar cells have been rising with the development of newer technologies. Today, the efficiency of the best Silicon mono-crystalline (Si-mono) solar cell at the time of writing has been reported to be about 24 % in controlled laboratories (Green *et.al.,* 1996) with commercial ones reaching up to 16 %. The highest conversion performance for a PV cell has been the GaPIn/GaAs multijunction cell which achieved an efficiency rating of 30.3 % in the laboratory (Green *et.al.,* 1996). The latest efficiency records of the performance of some of the PV cells are shown in Table 2.3:

Classification a	Eff.b %	Area c cm2	Voc V	Jsc mA/cm2	FFd %	Test Centre e (Date)	Description
Si (crystalline)	24.0	4.00 (ap)	0.709	40.9	82.7	Sandia (9/94)	UNSW PERL
Si (multicrystal)	17.8	1.0 (ap)	0.628	36.2	78.5	Sandia (3/94)	Georgia Tech
Si (thin crystal)	21.5	4.044 (ap)	0.699	37.9	81.1	Sandia (8/95)	UNSW
Si (thin film)	14.2	100 (t)	0.608	30.0	78.1	JQA (3/93)	Mitsubishi
GaAs (crystalline)	25.1	3.91 (t)	1.022	28.2	87.1	NREL (3/90)	Kopin
GaAs (thin film)	23.3	4.00 (ap)	1.011	27.6	83.8	NREL (4/90)	Kopin
GaAs (submod.)	21.0	16(t)	4.04	6.6	80	NREL (4/90)	Kopin
GaAs (multicrystal)	18.2	4.011 (t)	0.994	23.0	79.7	NREL (11/95)	RTI
CdTe (cell)	15.8	1.05 (ap)	0.843	25.1	74.5	NREL (6/92)	South Florida
CdTe (submod.)	10.5	83.4(ap)	9.406	1.72	64.9	FhG-ISE (2/95)	ANTEC
CIGS (cell)	16.4	1.025 (t)	0.678	32.0	75.8	NREL (11/94)	NREL
CIGS (submod.)	14.2	51.7 (ap)	6.808	3.1	68.3	JQA (10/96)	Showa Shell
a-Si (cell)g	12.7	1.0 (da)	0.887	19.4	74.1	JQA (4/92)	Sanyo
a-Si (submod.)g	12.0	100 (ap)	12.5	1.3	73.5	JQA (12/92)	Sanyo
GaInP/GaAs	30.3	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy
GaAs/CIS (thin)	25.8	4.00 (t)				NREL (11/89)	Kopin/Boeing
a-Si/CIGS (thin)g	14.6	2.40 (ap)				NREL (6/88)	ARCO
a-Si/a-Si/a-SiGeg	13.5	0.27 (da)	2.375	7.72	74.4	NREL (10/96)	USSC

Table 2.3: Confirmed terrestrial cell and submodule efficiencies measured under the global AM 1.5 spectrum (1000 Wm^{-2}) at 25°C (Green *et.al.*, 1996). a - CIGS = CuInGaSe2; a-Si = amorphous silicon/H alloy; b - Effic. = efficiency; c - (ap) = aperture area; (t) = total area; (da) = designated illumination area; d - FF = fill factor; e - FhG-ISE = Fraunhofer-Institute für Solare Energiesysteme; JQA = Japan Quality Assurance; f - Measurements corrected from originally measured values due to Sandia recalibration in January 1991; g - Unstabilized results.

2.1.3 Environmental aspects

Energy generated by PV systems is extracted from the ambient environment itself and poses no significant negative side-effects to it. There are no significant thermal or noise pollution and are inherently non-polluting (PViB Pack, 1995; Marshall, 1996; Lorenzo, 1994; Twidell and Weir, 1986).

The major advantages of PV technology include: abundance of fuel, little impact on natural eco-systems, technically proven and has been established, minimal public and occupational health risks, no moving parts with little maintenance and operation costs, modular in construction thus making it flexible and has a minimal water requirement during operation.

With regards to the environment, PV technology has been rated as the most environmentally benign of all electricity technologies envisioned for large scale global use, except maybe in terms of visual intrusion (PViB Pack, 1995). The negative effects of which have been rated from negligible to significant in terms of particulate, heavy metals, waste disposal and land requirement (Markvart, 1994). It has been noted that the major issues regarding the use of PV technology were: land use for arrays, visual amenity, waste disposal and hazardous gases during manufacture (PViB Pack, 1995; Markvart, 1994). While disposal of dated systems however need proper regulations, none of the impacts identified against PV appear prohibitive or insoluble (Taylor, 1990). A selected summary of comparisons between the conventional power producer and a renewable one is shown in Table 2.4:

Parameters	Renewable energy supplies	Conventional energy supplies
Examples of technology	Solar thermal, PV, wind	Coal, oil, gas
Source	Natural local environment	Concentrated stock
Initial intensity	Low, dispersed < 300 Wm^{-2}	High - 100 kWm^{-2} and above
Supply	Infinite	Finite
Location for use	Site and society specific	General and international
Safety	Local hazard in operation	Most dangerous when faulty
Aesthetics	Local perturbations	Large systems become unsightly

Table 2.4: Comparison of some of the advantages and disadvantages between conventional and renewable energy systems (Twidell and Weir, 1986).

Table 2.4 shows a very stark difference in terms of the supply of "fuel" for the renewable energies which is "infinite" as compared to the "finite" quantities of the conventional energy systems.

2.2 Integration of photovoltaics in buildings

2.2.1 The Concept

Traditionally, most modern energy-conscious built forms have been revolving around innovative concepts in passive solar architecture. These have included super-designs in thermal, ventilation, daylighting and shading manoeuvres, especially in the urban built environment. These sustainable technologies, except for active solar thermal, at best, only optimise the total energy balance of a building; i.e. targeting to have a net zero energy balance. With the advent of Building integrated PhotoVoltaics (BiPV) technology, this concept of energy-conscious built-form is being phased into a new dimension. Instead of just being a passive design, BiPV technology offers the mechanism of crossing-over into the realm of becoming an active solar architectural built-form and back again, providing more options than others can, with style and full of aesthetics.

Traditionally, a PV system can be generally defined as an integrated assembly of modules and other components, designed to convert solar energy into electricity to provide a particular service, alone or with backup (Treble, 1991). With the concept of building integration of PV modules, BiPV can be generally defined as the art of scientifically assimilating PV systems into the built environment to gain traditional benefits as well as offering synergistic and aesthetic advantages. This can be achieved by architecturally integrating the modules as part of the building envelope itself. The PV modules may be manufactured as roof tiles, overcladding, shading louvers or even forming the facade or roof altogether. BiPV technology can be applied to all PV applications, for stand-alone, hybrid and grid-connected or grid-interactive systems.

2.2.2 The Benefits

Built-forms with BiPV systems is a relatively new technology and is ideally suited for facades and roofs (Schmid, 1994). With proper architectural designs and the development of newer technologies, it has been growing steadily, producing electric power for the building, enhanced with aesthetics whilst maintaining traditional, as well as modern building envelope performance requirements. Issues relating to BiPV architectural designs have to include the general aspects of the; a) aesthetic requirements, b) structural, electrical and mechanical designs, and c) multifunctionality of the PV modules, which requires proper designs so as to optimise benefits and minimise costs.

Shading and daylighting are the main obvious benefits related directly to the energy aspects of BiPV technology. These two forms are the popular modes of integration and have benefited buildings in many BiPV installations in the Northern latitude countries. Having the PV modules ingeniously installed in the building, directly influence the amount of shading and daylighting entering the building. This feature not only provides electrical power directly, but also alters the patterns of energy demands and consumption in the building itself. Several studies were being pursued within the scientific and technological community, regarding aspects of these synergistic benefits in BiPV installations, specifically with regards to the shading and daylighting issues in Northern latitude countries (Hendriksen, 1997; Madsen, 1994).

The popular applications of BiPV technologies have been in the following forms (Hestness and Andersen, 1997; Benemann and Chehab, 1996; Sick and Erge, 1996; Marshall, 1996; PViB Pack, 1995; Strong, 1995; Scott, 1994; Humm and Toggweiler, 1993);

- Roof tiles or panels.
- Shading panels (shadowvoltaics).
- Rainscreen overcladding.
- Curtain walling.
- Window facade.
- Rooflight and atria.

These existing types of BiPV design configurations can be generally classified into the categories as follows (Sick and Erge, 1996; PViB Pack, 1995; Humm and Toggweiler, 1993):

2.2.2.1 *Roofs and coverings*

This type of configuration comes in the forms of modular roof tiles, PV glazing of partial roof areas (e.g. skylights) or total coverings of the roof (e.g. atria). Particular issues involving this type of integration include: loading from rain, snow accumulation or hail with a compromise in optimum tilt angle. Alternatively, the PV modules may not actually replace traditional roofing materials, but are merely attached to the roof structures. This choice of integration eliminates technical problems associated with having to deal with new and alien technology to builders.

2.2.2.2 *Walls and facades*

There are two basic types in use: i) pressure plate and ii) structural silicon glazing. In type (i) the glazing material are mechanically held by supporting structures. In type (ii) the silicon glazing edges are glued to the framing structures. Alternatively the PV modules may be supported by external structures that are in turn, attached to the main building structure. There is also an air gap between the PV facade and the actual building fabric which provides the added advantage of naturally ventilating the PV facade.

2.2.2.3 *Light filtration and screening elements*

These come in the forms of opaque PV panels installed as awning devices, light shelves or as semi-transparent windows. Design of the integration is dictated by the permutational requirements of the amount of power generation, shading and daylighting levels inside the building. In this case, the PV cells are placed side by side to each other in a matrix, with spaces in between them to allow passage of light. Major issues for this type of integration include the amount of daylight permitted into the room as well as the view angle towards the external as seen from inside the building.

The systems discussed in the preceding parts have been possible due to the modular design and structure of the PV components and better technologies of power conditioning. In fact, BiPV systems offer an added value in many forms especially aesthetics and the elimination of land and higher materials costs. The major advantages of these systems are (Leppanen and Spiers, 1997; Sick and Erge, 1996; Marshall, 1996; PViB Pack, 1995; Schmid, 1994; Toggweiler, 1994; Taylor, 1990):

- Design of buildings are already suitable for PV integration.
- The size and area of a building are suitable and available.
- Energy demand is in phase with PV power production for many buildings.
- Elimination of isolated supporting structures, mechanical planning, installation and land area.
- Reduction in transmission and distribution losses.
- Improved aesthetics and symbol of statement.
- Environmentally benign.

However the costs above are replaced by costs of the: a) PV modules, and b) Balance of System (BOS) comprising of components other than the PV modules, like cabling and power conditioning equipment.

2.3 Selected BiPV literature review

2.3.1. Global review

A search made on BiPV literature reveals that at present, a concerted and systematic effort has been established for the dissemination and appreciation of BiPV technology specifically. This establishment is the International Energy Agency (IEA), formed in 1974 with the aims of carrying out programmes of energy cooperation, joint research and development of new and improved energy technologies. Member nations include Austria, Canada, Finland, Germany, Italy, Netherlands, Norway, Japan, Spain, Sweden, Switzerland and the UK, with the EU and the USA as observers. Of special interest is the Solar Heating and Cooling Program (SHCP) formed in 1974. In this program, a specialised program called Task 16, signed in 1990, deals specifically with Photovoltaics in Buildings (McNelis *et.al.*, 1996; Sick and Erge, 1996; PViB Pack, 1995). Task 16 deals with both the architectural and engineering aspects of integrating PV systems into buildings, or simply BiPV technology. A design handbook for architects and engineers, specifically for BiPV systems has now been made available by the IEA (Sick and Erge, 1996). At the time of writing this was among the first published textual guideline handbook on BiPV technology, produced by an international co-operative body. Another IEA BiPV program is the Photovoltaic Power Systems Programme (PVPS) which was signed in 1993. Projects within the PVPS include: a) information exchange and publications, b) operational performance and database, c) stand-alone systems, d) modelling of PV-grid support, e) grid interconnection of BiPV systems, f) modular large-scale PV plants, and g) BiPV technology generally.

Historically, BiPV technology was realised in a practical building in the early 1980's. There are now numerous demonstration sites aimed at promoting and establishing the technology in proving its applicability, practicality and benefits, especially in the more Northern latitude countries. There are also many public-funded researches, tests, developmental and computerised on-line sites for BiPV technology dissemination. Various member countries in the IEA have been providing encouragement or subsidies in one form or another, to promote and incite its acceptance and eventual proliferated use amongst their citizens. A summary list of several existing BiPV sites outside the UK is shown in Table 2.5:

Site	Year	Capacity	Description (type of application)
Carlisle House, Boston, USA	1981	7.3 kWp	residential roof
Georgetown University, USA	1983	300 kWp	non-domestic roof
Rokko Island, Japan	1986	2 kWp x 100	residential roof
DEMOSITE, Lausanne, Switz.	1992	8 kWp	several combinations of integration
Scheidegger Metalbau, Switz.	1992	18 kWp	sunshade awning
PMS Energie, Switz.	1992	3 kWp	roof tiles
Bayer. S. Ministerinen, Germany	1993	53.4 kWp	office shading device
Solarzentrum, Germany	1993	18.5 kWp	facade and roof
Brundtland Centre, Denmark	1994	1.5 kW	translucent PV atrium and facade
ELSA Building, Ispra, Italy	1994	25 kWp	facade
Solar One, Australia	1996	1.3 kWp	residential roof
Lugano Building, Switz.	1997	180 kWp	office roof, sunshade and facade

Table 2.5: Selected BiPV sites and types of applications, outside the UK. kWp - kilo-Watt peak capacity.

Table 2.5 shows that the first documented practical BiPV application was realised within the last two decades in the USA, which is an indication of its relative age of technology. This development was followed by the Japanese, and the Swiss and the Germans were amongst the first to use BiPV technology in Europe.

BiPV technology can now be said to be recognised throughout the industrialised countries and experience in PV grid connected systems are now available in the USA, many European nations, and Japan (EREN-DOE, 1998; FSEC, 1998; Hestness and Andersen, 1997; PVPOWER, 1997; Sick and Erge, 1996; Whalley, 1996; EUDG XVII, 1995; PViB Pack, 1995; Strong, 1995; Hill, 1994; Markvart, 1994; Open University, 1994; Pearsall *et.al.,* 1994; Toggweiler, 1994; Derrick, 1993; Halcrow Gilbert, 1993; Humm and Toggweiler, 1993; REAG, 1993; Strong and Scheller, 1993; Taylor, 1990; Green *et.al.,* 1983; Macomber, 1983; Wrixon, 1983). This can be seen clearly as member nations of the IEA embark upon BiPV programmes in their respective nations with considerable targets. Amongst the more well-known programmes are the American “Million Roof Solar Initiative”, the Japanese, “Sunshine” programme, within Europe, the German “1000 Roofs Programme”, the Swiss “Energy 2000” programme, and the Dutch “BiPV housing scheme”.

The USA has a large PV following with the implementation of the “Million Solar Roof Initiative” (DOE-USA 1997). The US Department of Energy has a network of links that form a web of BiPV working ends. Amongst the more well-known centres are the Center for Renewable Energy and Sustainable Technology (CREST), the Florida Solar Energy Center (FSEC), the National Renewable Energy Laboratory (NREL), the Sandia National Laboratory and many other municipal districts, entities and universities that focus on PV and BiPV technologies. The government also has a special programme that links utility companies called the “Utilities PhotoVoltaics Group”. Standards of measurements have been developed, tested and institutionalised in the ASTM E 1036 and further improvements have been proposed (King, 1998). The American efforts in BiPV technology have been wide ranging from cell development all the way to numerous practical installations. It now appears that the scientific and engineering aspects of BiPV technology have been well established in the USA. There are programmes aiming at proliferating its use by offering incentives in many forms as illustrated by the Sacramento Municipal Utility District (EREN-DOE 1998). Two major issues have been observed to be emphasised widely regarding the American

BiPV applications, which were: a) cost of generation and b) working mechanisms to achieve widespread use. The Americans have also been extending non-BiPV technologies in many parts around the globe, especially in the developing nations (CADDET-USA Technical Brochure no.26, 1995; Sheppard and Richards, 1998; Strong and Scheller, 1993).

In Japan, the development of PV technology can be traced back with the start of the "Sunshine Project" in July 1974. Its first grid-connected system of six projects was started in 1980 along with its first centralised PV power system at 1430 kW peak (kWp) capacity. Its first roof integrated PV modules for residence was built in 1985 and a much stronger and bigger array system was built in 1989. Finally its first complete utility-style installation was built in Rokko Island with 2 kWp x 100 houses in 1986. Japan has been involved with the IEA Task V of PV R&D programme since 1993 (Kurokawa 1996). The Japanese have also been doing research and developmental work across the spectrum from cell development to BiPV technology applications (Ishikawa, 1996; Wakamatsu and Nitta, 1996). Various on-line computer internet sites showing the Japanese installations are presently made available from Japan (NEDO Homepage, 1994).

Within Europe, the Commission of European Communities (CEC) runs the DG XII Solar House II Programme to promote solar architecture. International forums for developing international standards for PV modules and systems are the ISO and CENELEC. Uniform monitoring of PV systems generally, have also been established for conformity throughout the world (JRC Ispra, 1997; Imamura *et.al.,* 1992).

In Germany, culminating from experience of the first BiPV use for the "Solar House" in Freiburg, a more advanced and comprehensive treatment of the BiPV system performances have been published for the "German 1000 Roof Programme" (FhG-ISE, 1996 and 1995). The publications presented comprehensive, detailed and specific issues relating to practical performances and average costs. In summary, there are now up to about 5.9 MWp of installed BiPV system capacity. The installations in the programme have an average PV array size of 2.64 kWp capacity per house, with various different orientations and tilt angles. The installed cost was about US$ 16.81 per Wp.

The average system performance gave an average final yield of 700 kilo-Watt-hour per kilo-Watt peak capacity ($kWhkWp^{-1}$) p.a. and an average array yield of 1.9 kilo-Watt-hour per day per kilo-Watt peak capacity ($kWhd^{-1}kWp^{-1}$) p.a., based on an average solar input of 928 kilo-Watt-hour per metre square ($kWhm^{-2}$) p.a. It gave an average PV conversion efficiency rate of 8.7 % and a Performance Ratio (PR) of 65 %. The major issues faced in the German experience related to: a) partial shading of the modules, b) defects in the DC electrical installations i.e. defects in the modules, diodes, terminals and connections, c) inverter problems i.e. inverter breakdown, control electronics, operating voltage window and mismatch due to partial shading of the modules, and d) grid-connection i.e. galvanic isolation systems. An on-line performance display through the computer showing the hourly values from several sites in Germany are now available for the world-wide dissemination of knowledge (FhG-SONNE-online, 1998).

In Switzerland, the applications of BiPV technology can be seen in numerous practical systems throughout the country within the “Energy 2000” programme which is being spear-headed by the Swiss government (Swiss Federal Office on Energy Homepage, 1998). Switzerland has up to 2 MWp of installed PV capacity and has a target of 50 MWp installed capacity by the year 2000. It has been one of the earlier users of grid-interactive BiPV technology in Europe, with various practical experiences disseminated in various publications (Clavadetscher and Nordman, 1993; Keller and Affolter, 1995), including on-line technology through the internet (EPFL Homepage, 1995). One of the earliest commercial European publications on BiPV technology in architecture was from Switzerland (Humm and Toggweiler, 1993). Presently, an hourly on-line display of system performances of the various Swiss sites are available through the internet (METEOTEST PV-Monitor, 1998).

The Netherlands has also been making significant strides in the applications of BiPV technology. This is illustrated by its “BiPV Housing Scheme”. One of the projects involves the first large-scale household integration in urban areas in Amsterdam’s Nieuw Sloten. This is a 250 kWp PV system involving 71 new residential homes (PVPOWER, 1997). Another urban PV integration programme is the 1 MWp grid-connected system in Amersfoort.

Other countries in Europe that have significant PV and BiPV systems installed include: Italy, Austria, Spain, Denmark, Finland, Sweden, Norway, Portugal and France.

Specialised treaties on PV technology generally are in abundance and publications in scientific and technical journals are on-going. There are numerous literature on PV itself such as, PV physics, modules, systems design, simulations, data-logging of PV systems, types of applications and problems, prospects, markets, economics and projections, BOS components and design and related topics, all for terrestrial as well as extra-terrestrial applications. General publications regarding BiPV systems that have been reviewed, presented mostly the conceptual ideas, demonstrations and photographs, general overviews and modes as well as issues of integration on practical installations (Hestness and Andersen, 1997; Lund and Peippo, 1997; Hagemann 1996, Sick and Erge, 1996; PViB Pack, 1995; Strong, 1995; Hestness, 1994; Stahl *et.al.*, 1994; Humm and Toggweiler, 1993; Strong and Scheller, 1993). Several publications presented the overall performance of solar low energy buildings with facts and figures on energy-savings (Nieminen and Kouhia, 1997; Schmid, 1994). Other publications presented the basic economics of BiPV applications (Leppanen and Spiers, 1997; PViB Pack, 1995; Schmid, 1994; Palz, 1978). A few literature publications presented discussions on the synergistic benefits of BiPV technology such as daylighting and energy-savings (Sick and Erge, 1996; Madsen, 1994; PViB Pack, 1995; Hendricksen 1994). Several textual publications presented more comprehensive discussions with regards to BiPV sizing and related issues and were found to be very useful (Sick and Erge, 1996; Strong and Scheller, 1993) Several publications presented simulative and practical aspects of thermal-based performances for BiPV integration and generation (Brinkworth *et.al.*, 1997; Clarke *et.al.*, 1997; King, 1997; Hankins, 1995; Mosfegh and Sandberg, 1995; Markvart, 1994; Groehn, 1993; Strong and Scheller, 1993; Overstraeten and Mertens, 1986; Twidell and Weir, 1986; Green, 1982; Palz, 1978). All of these publications stated that the temperature elevation of these modules negatively affected the PV performances. Others presented aspects on shading of the PV panels (Spratt *et.al.,* 1997; Quaschning and Hanitsch, 1996; Kovach, 1994; Gabler *et.al.*, 1993; Overstraeten and Mertens, 1986) as well as dust accumulation (El-Shobokshy and Hussein, 1993).

These literature analysed the mathematical models of partial shading on the PV modules. However, these thermal-based analyses and shading aspects of the BiPV performances were simulated for more Northern climate latitudes. It was reported that both the thermal and shading issues influenced negatively the system performance of BiPV installations. Thus these thermal and shading issues would need to be addressed in any prospective BiPV applications. Several analytical computer models have now been developed to cater for these issues. A literature review and corresponding discussion of some of the available computer models of interest for this research project are presented in a later Chapter. Other types of publications such as newsletters and proceedings are continuously being published and distributed. Various websites in the internet on PV issues and introductory mentions of BiPV are also available, maintained by corporate, private companies and individuals from different countries throughout Europe and the USA. However, none of these presented publications have actually presented or discussed in detail, studies or extensions of BiPV applications in the sunnier climates of the developing nations that lie within the lower latitudes of the globe.

Amongst the many developing nations of the world, there are many thousands of PV installations in all of the habitated continents of the world. Within the region of interest in this research project, i.e. South-East Asia (SEA), there have been numerous PV powered applications; e.g. within the rural electrification programme of the United Nations Industrial Development Organisation (UNIDO) involving Malaysia, Indochina and India (Thompson and Singh, 1996). In addition, large numbers of PV power systems have been installed in Indonesia (Novem, 1998; PVPOWER, 1997; Mostavan and Wasigaren, 1990), the Philippines (CADDET-USA Technical Brochure no.26, 1995; RERIC, 1995a; de Bakker, 1990), Vietnam (CADDET-USA Technical Brochure no.28, 1996) and Thailand (RERIC, 1995b). The literature on Malaysia is presented and discussed in detail in a later Chapter. The latest development in the SEA region, was a particular plan in Thailand proposing to grid-connect an existing 60 kWp PV array to the 22 kV distribution system (Kruangpradit and Tayati, 1996). However, this system had not been planned to be building integrated. The closest study that parallels the interest of this research project was a proposed investigation in Hong Kong on the integration of PV in high rise buildings (Close, 1996). However, this proposal emphasised legislative issues with regards to PV applications in high rise buildings in Hong Kong and no details of the investigation with regards to the size of the array and techniques of integration were given in the published literature. It was generally found that none of the reviewed publications presented BiPV applications in the developing nations in SEA, as well as in other developing regions of the world that were directly building-integrated and grid-interactive technology.

The closest practical BiPV installation to the region of interest within this research project is in Australia (Green, 1998; Watt *et.al.,* 1997b; CADDET-Australia, 1997; CADDET-Australia, 1996; Kaye *et.al.,* 1997). The first Australian residential BiPV application is the "Solar One" in Queensland, launched in 1996 (CADDET-Australia, 1996). It has a capacity of 1.3 kWp using sixteen Solarex 83 Wp modules. It consists of two sub-arrays with eight modules connected in series. Each sub-array produces an output of 96 V DC. The inverter used is a 240 V AC at 1.5 kVA and manufactured by Butler/Siemens. The designed PV generation was 6 to 8 kWh per day which would give a yield of 1,924 $kWhkWp^{-1}$ p.a. or an array yield of 5.3 $kWhd^{-1}kWp^{-1}$ p.a. The installed cost was US$ 10,000 giving a rate of US$ 7.69 per Wp and the 150 m^2 building cost was US$ 80,000 with a cost of generation at US$ 0.17 per kWh. This is considered to be "highly competitive". Another BiPV installation in Australia is for a residential house in "Discovery Park", New South Wales. It has a rated capacity of 0.9 kWp PV using twenty-seven Swiss made roof tiles at 37 Wp each. The tiles are arranged in an array comprising of three strings, with each string having nine tiles connected in series. The operating voltage is 100 V DC. The inverter used is a 2.5 kVA single phase grid-interactive manufactured by an Australian company. The array produces approximately 4 $kWhd^{-1}kWp^{-1}$ p.a. which gives a yield of 1,461 $kWhkWp^{-1}$ p.a. and can be considered as excellent. The back of the PV tiles are uncovered for heat dissipation. Additional ventilation of the roof space is achieved using under-eaves vent and a vent cap at the roof ridge provides further ventilation. However, details of these treatments i.e. the thermal-based analysis have not been made available nor published at the time of writing. The PV tiles costed between ten to fifteen times as much as conventional roofing material. The energy output was about 110 Wp per m^2. The total cost was about US$ 600 per m^2. The installed cost was US$ 10,000 giving a rate of about US$ 11.13 per Wp. (CADDET-Australia, 1997). The estimated cost of generation was about US$ 0.28 per kWh. These

Australian BiPV performances are among the best available and these experiences provide valuable insight for this research project.

2.3.2 BiPV-UK review

2.3.2.1 PV development in the UK

Work into the research and development (R&D) of PV cells have been going on in the UK since the 1960's and 1970's. A brief historical note has been published relating to this development (Gregory and McNelis, 1994; Riddoch and Wilson, 1981). One of the earliest literatures in the UK with regards to assessment of solar energy for the UK has been published by the UK-ISES in 1976. In the 1980's, the Newcastle Photovoltaics Application Centre (NPAC), at the University of Northumbria was established. BP Solar built and monitored a 30 kWp grid-connected PV pilot plant at Marchwood and at about the same time, a 50 kWp PV system powering a dairy farm in Ireland was built (Gregory and McNelis, 1994; Wrixon, 1983). The first use of PV to power repeater stations in Scotland was in 1975 (Riddoch and Wilson, 1981). It was generally felt that the evolution of PV technology and applications in the UK especially relating to the UK government involvement, has been slower than most other leading nations. Most literature publications presented and discussed the potentials, prospects and criticisms on the applications of PV and BiPV applications in the UK generally. One publication stated that "although the UK has an extra-ordinarily high percentage of internationally-acclaimed PV experts, it has a largely under-developed home market" (Wolfe, 1996). Another publication seemed to extend this further by stating that "the industry in UK presently suffers from lack of government support" while at the same time "has an expert science, technology and commercial base in PV" and "presently has a small home market" (McNelis *et.al.*, 1996). It was generally felt that the UK was trailing behind in the building and monitoring of demonstration projects for PV and that "the UK government has shown little foresight in this respect" (Roaf, 1997). This seemed to be to a certain extent, a corroboration of the general view and feeling that "PV is unlikely to have a significant contribution to electricity", compounded with "economic unattractiveness due to solar incidence levels in the UK" (Taylor, 1990; Gregory, 1987) and that "PV should be considered in residences and communications in sunnier climate countries" (Gregory, 1987). A working group concluded that "PV is seen as having a huge potential world-wide although a more modest one in the UK and the government is urged to contribute to the global R&D for this technology" (REAG, 1993). Another publication concluded that "awareness of PV technology in grid-connected applications is very limited in the UK" and went on stating that "the UK is lagging behind much of Europe in creating knowledge and general awareness of PV in grid-connected operation and in disseminating that knowledge" (Halcrow Gilbert, 1993). However, BiPV was seen as sensible in augmenting the mains as grid-connected systems (Hill, 1994; Taylor, 1990; Gregory, 1987). Certain publications cited that the UK "has an enormous potential for architectural integration of PV into buildings" (PViB Pack, 1995). Another publication cited that "PV was the only renewable to make the key opportunity list" with regards to renewable energy technologies in the UK (Archer, 1996). It was also reported that "presently, the UK has a small home market for PV technology but it has a 10 % share in the global market" (McNelis *et.al.*, 1995) and the projected installed PV capacity for the UK was 50 GWp by the year 2020 (McNelis *et.al.*, 1995).

The UK government's funding into PV research is through the Department of Trade and Industry (DTI) and the Engineering and Physical Science Research Council (EPSRC). Until recently, the UK government has realised its lack of role and has announced a £10 million funding for cleaner technology through its "Foresight Programme" (DTI Press Notice, 1997). The DTI channels its funds through the Energy Technology Support Unit (ETSU) and the EPSRC channels its funds through the "Clean Technology Programme" in 1995 with a budget of £1.3 million for PV technologies. Some BiPV-related researches in the UK funded by the EPSRC are as follows (Thomas, 1996):

- *Low-cost integral non-imaging concentrator PV building facades* - 1996
- *PV roof tiles: Design and integration in buildings* - 1996
- *Optimisation of PV cladding, planning and installation procedures* - 1996

Recently, in the UK, an educational programme called the "SCOLAR Programme" for photovoltaics in the UK was launched on 13 December 1997, by the then Minister responsible for renewable energy. The SCOLAR programme is for PV generally and is supported by the "Foresight Challenge Programme". It came about "as a strategy to prepare younger generation to meet up to the challenges of a key technology in the future and to keep up the lead by British scientists in the area" (DTI Press notice, 1996). Briefly it is a scheme to install PV solar panels in up to 100 British schools with funding from the government at £1 million (DTI Press notice, 1996). These schools are offered a discount of 65 % towards the use of solar electricity. Parties involved comprise of: a) the government b) academia and c) industry. The programme is targeted at improving the: a) technology development, b) implementation of PV systems in schools, c) dissemination of information. The parties involved in the programme, at the time of launching are listed in Table 2.6:

Beacon Energy Ltd.	Building Research Establishment	Colt Group
Co-operative Bank	Loughborough University	Dulas Ltd.
Earth Centre	Eastern Electricity	Cardiff University
Env. Change Unit @ Oxford U.	Halcrow Gilbert and Associates	Intersolar Group
IT Power	Northumbria University	Open University
Ove Arup	Rednet	Pilkington Technology
Schuco International	Sollatek	Southampton University

Table 2.6: Participants of the SCOLAR programme in the UK at the time of launching in December 1997.

Presently, a common platform for all parties interested and involved in PV and related matters within the UK is available and has been called the "British Photovoltaic Association" (PV-UK). Programmes in the UK relating to PV can be found in the EPSRC, DTI through ETSU, Foresight Challenge and SCOLAR. There are also research links with parties outside the UK such as the IEA and European Union Directorate General (EUDG) and working platforms like CADDET, JOULE-THERMIE and ALTERNER programmes. A database of other parties, institutions and companies with interest in renewable energy issues are available, such as Altechnica, UK-ISES, Greenpeace-UK.

2.3.2.2 BiPV in the UK literature review

It has been reported that BiPV technology is seen as having an enormous potential as well as most promising for new buildings in the UK (PViB Pack, 1995; Hill, 1994; Taylor, 1990). BiPV technology in the UK (BiPV-UK) was introduced in the 1990's, which is about a decade later than other leading nations' involvements. The earliest practical BiPV-UK system was for residential use, in Nottinghamshire and literature on the installation was published in 1994 (Vale and Vale, 1994;

Financial Mail, 1995). Since then only a handful of other BiPV-UK systems have been installed. Most BiPV-UK literature presented, discussed and gave descriptions of the respective BiPV systems, their generations and overall performances (Dichler, 1997; Noble, 1997; Pearsall *et.al.*, 1997; Trimby, 1997; Wade, 1997; Fuentes *et.al.*, 1996; HAC, 1996; Wade, 1996; PViB Pack, 1995; Simmons, 1995; Hill, 1994; Roaf, 1994, Pearsall *et.al.,* 1994; Vale and Vale, 1994). However, most of the presentations were without certain basic performance indices and did not totally conform to the format of the JRC in Ispra. Only a few of the publications specifically analysed and presented the overall performance comprising of real measured data, such as measured solar irradiances, conversion efficiencies and Performance Ratio (PR) of a practical BiPV-UK installation (Dichler, 1997; Pearsall *et.al.,* 1997). Other UK publications presented techniques relating to the design of PV systems (Open University, 1994; Treble, 1991) and estimates in solar energy capture and conversion efficiencies of PV's (Sayigh, 1991). Other publications discussed more technical aspects of PV and grid connection systems (Simmons and Infield, 1996; Munro and Thornycroft, 1997; Halcrow Gilbert, 1993). Several publications described technical aspects of PV such as system design, wiring and grid-connection issues such as codes and requirements for grid-connections (Bates, 1996; Simmons and Infield, 1996; Hacker, 1994; Halcrow Gilbert, 1993) and shading issues (Spratt *et.al.*, 1997). Several UK authors presented theoretical and practical aspects of thermal-based PV performances (Brinkworth *et.al.*, 1997; Clarke *et.al.*, 1997; Twidell and Weir, 1986; Markvart, 1994). Others gave descriptions of installation experiences (Wade, 1997 and 1996) and monitoring systems and methodology (Child, 1995; Dichler, 1993; Treble, 1991).

Other UK literature presented and reported the basic economics of PV and BiPV-UK systems (McNelis *et.al.*, 1996; Crick *et.al.,* 1994; Financial Mail, 1995; David, 1996; Simmons, 1995; Pearsall, 1995; Roaf, 1994; Taylor, 1990). Only a few of these publications presented and discussed options and experience of the other part of the BiPV system, which was the integration part in BiPV (Jones, 1996; Marshall, 1996; PViB Pack, 1995). However, none of these literatures actually discussed the technical aspects and evaluations of synergistic benefits such as shading, daylighting and details of energy-savings. Several authors presented PV programmes in the UK (McNelis *et.al.*, 1996; Cole, 1994; Halcrow Gilbert, 1993) and comparative notes on programmes in the UK against others within the European community (Roaf, 1997; Halcrow Gilbert, 1993). Other publications discussed the overall concept of PV and BiPV technologies and their general overviews and certain economic considerations (Noble, 1997; Open University ,1994). Several commercial and non-commercial publications in the form of complete books or chapters in books relating to PV have been written by UK authors (Hankins, 1995; PViB Pack, 1995; Open University, 1994; Markvart, 1994; Halcrow Gilbert, 1993; Roberts, 1991; Dunn, 1986; Twidell and Weir, 1986; Treble, 1991; Wilson, 1979) while UK publications on PV and related issues in the form of bounded proceedings numbered much more.

It is noted that none of the published BiPV-UK experience have actually involved any exploratory application studies for sunnier climate countries in the developing nations, in the lower latitudes of the globe.

2.3.3 BiPV-UK site installations

The UK BiPV experience seems to be very lacking as compared to other industrialised nations in terms of the availability of practical sites. Up to the time of writing, the commissioned BiPV sites in the UK is eight, with only two of the sites having published technical performance results. At the time of writing, the major PV grid-connected systems in the UK are as follows:

2.3.3.1. Southwell, Nottinghamshire

This residential building is the first privately-owned UK grid-connected PV installation and was commissioned on July 27 1994. The system has thirty-six 60 Watt Solarex MSX-60 polycrystalline panels, and are arranged in two rows of eighteen panels each. This gives a peak capacity of 2.16 kWp. The panels are connected in series strings of six modules, with each string giving an output voltage of 102 V DC. Output to the grid is via an SMA PV-WR1800 inverter rated at 1.8 kW and metering is done using two standard mechanical meters. The energy output from the PV system obtained from the inverter for 1995 was 1,762 kWh p.a. or 820 $kWhkWp^{-1}$ p.a. (Wade, 1996) which gives an array index of 2.2 $kWhd^{-1}kWp^{-1}$. The installed cost was about US$ 12.75 per Wp (Vale and

Vale, 1994) with an estimated generation cost of about US$ 0.80 per kWh (Simmons, 1995). The South-facing PV array is mounted on a pergola and is not directly integrated into the residential building. The whole autonomous residential low energy building came with a construction cost of about US$ 935 m^{-2} (Financial Mail, 1995). No systematic on-going data logging work has been set-up at this site.

2.3.3.2. Newcastle Photovoltaics Applications Centre, Northumbria University, Newcastle

The Newcastle Photovoltaics Applications Centre (NPAC), of the University of Northumbria, is the UK's first large scale (greater than 10 kWp) grid-connected BiPV installation. It has a capacity of 39.5 kWp and was commissioned in January 1995. The building is a five-storey office block in the city centre campus of the university. The North and South facades of the building were in need of refurbishment due to deterioration and it was decided that they would be resurfaced with PV cladding. The PV cladding has 465 BP Saturn 85 Watt monocrystalline silicon PV modules connected in strings of fifteen panels in series, with each string giving a voltage of 270 V DC. Altogether there are thirty-one strings connected in parallel. Grid-connection is via a 40 kW line-commutated thyristor inverter with input voltage at 270 V DC and output at 415 V AC, three phase. The PV power generation has not been expected to meet the building's demands but was estimated to provide about a third of the building's requirements p.a. The panels are South-facing, integrated into the building facade, inclined at 75 degrees from the horizontal. The PV panels have been estimated to suffer a shading fraction average of 25 % of the total area (Pearsall *et.al.,* 1997). The total cost of installation was US$ 2.55 million and the cost of electricity produced was between about US$ 0.40 to 1.16 per kWh (CADDET-UK Technical Brochure no.67, 1998; David, 1996; PViB Pack, 1995; Simmons, 1995) with a lifetime of 30 years. The BiPV installation at NPAC costed US$ 700 per m^2 for the PV modules alone, US$ 355 per m^2 for the BOS costs and US$ 468 per m^2 for the rainscreen cladding (David, 1996). The total cost of the PV cladding came to about US$ 1,523 per m^2. The yield from January 1995 till March 1997 was 43,863 kWh (Pearsall *et.al.*, 1997). This gives a yield index of 492 $kWhkWp^{-1}$ p.a. or 1.35 $kWhd^{-1}kWp^{-1}$ with a global solar irradiation of 2.31

$kWhm^{-2}$. These values seem realistic for such a BiPV installation in the UK climate. Computerised data logging are being done every minute in accordance to the international standard of JRC, Ispra 1993. An average PV conversion efficiency of about 8.1 % and an average monthly inverter efficiency of 90 % have been recorded for the BiPV-NPAC system. The Performance Ratio (PR) of the system has been calculated to be at 61 % and the panel temperature had a peak temperature of about 60 °C with an average of about 15 °C above the ambient for sunny days (Pearsall *et.al.,* 1997). This BiPV-NPAC system has been the UK's most publicised installation throughout the PV community in the UK. Analysis of the system performance is on-going.

2.3.3.3. Angela Marmont Renewable Energy Laboratory Building, Loughborough University

The Angela Marmont Renewable Energy Laboratory (AMREL) building is a non-BiPV installation consisting of a grid-connected thin-film amorphous silicon 2.156 kWp PV array mounted on the roof of its building using a rack mounting. The system was commissioned in 1995. The array is divided into two sub-arrays, with each sub-array having fourteen parallel strings. Each string has seven modules connected in series, using 11 Wp Intersolar Phoenix amorphous Silicon thin film modules. Output from the two sub-arrays is connected to a single phase line-commutated SMA PV-WR1800 inverter rated at 1.8 kW. Each PV sub-array produces 1,078 Wp at 105 V DC and 10.3 A DC and is fed into a three phase wiring of the building. A separate data logging system has been installed for the PV grid-interactive system. The installed cost was about US 16.53 per Wp and the generated energy cost was about US$ 1.12 per kWh (Simmons, 1995). At the time of writing, analysis of the system performance is still on-going.

2.3.3.4. Whittle Hill Farm Office Buildings, Beacon Energy Ltd., Nanpantan, Leicestershire

This BiPV office building is the subject of the practical phase in this research programme. Details of the BiPV system, data logging equipment and overall performance analysis are presented in this thesis.

2.3.3.5. The Oxford Ecohouse, Oxford

This installation is an urban residential five bedroom bungalow combining uniquely active BiPV technology and low-energy architecture design. The system has an array of 4.08 kWp PV modules that form its South-facing roof and is grid-interactive via a 5 kW single phase SMA PV-WR inverter. The system was commissioned in 1995. The annual energy consumption of the house was 2,131 kWh p.a. and the output from the PV generation was 2,937 kWh p.a. The installed cost of the PV was US$ 9.17 per Wp and the generation cost has been estimated to be between US$ 0.44 to 0.97 per kWh (Dichler, 1997; Simmons, 1995; Roaf, 1994). The calculated system performance of the installation gave a final yield of 2.3 $kWhd^{-1}kWp^{-1}$ which is the highest amongst all of the BiPV-UK existing systems. The inverter efficiency was about 80 %, the system conversion efficiency was about 8.4 % and the PR was about 63 %, (Dichler, 1997). The installation has been experiencing higher temperatures on some of the cells with peak array temperatures reaching up to 73 ^{o}C, which is considered to be very high in the UK climate.

2.3.3.6. Homerton Grove Playground, Hackney

This recreation building consists of BiPV roof tiles tilted at 40 degrees from the horizontal. There are forty-five 36 Watt Swiss-made Newtec AG roof tiles, giving a peak capacity of 1.62 kW. The system was commissioned in 1996. The array feeds 120 V DC to an SMA PV-WR1800 inverter rated at 1.8 kW and is connected to the single phase consumer unit (Wade, 1996). No further details have been made available at the time of writing.

2.3.3.7. Southampton University, Southampton

This is a 3.4 kWp non-BiPV array on top of a university building. The modules are rack mounted, with variable inclination angles from 30 to 90 degrees from the horizontal. They are grid-connected and the arrays have been arranged in five strings of 72 V DC each (Arnold, 1996). The system was commissioned in 1996. No further details have been made available at the time of writing.

2.3.3.8. Centre for Alternative Technology, Wales

The Centre for Alternative Technology (CAT) building is the latest BiPV project in the UK and was commissioned in 1997. The centre is a demonstration site located in Wales for alternative energy sources. Amongst the renewable energy technologies installed are the 13.5 kWp PV panels on the roof of the CAT building. There are 180 BP Solar 275 modules making a total panel area of 112 m^2 and has been estimated to produce 9.6 MWh of electrical energy p.a. (CADDET-UK Technical Brochure no.71, 1998; Solar News, 1996). There are altogether fifteen PV strings and each has twelve modules connected in series. The total cost of the project was US$ 217,600 with the cost of generation estimated at US$ 0.64 per kWh (CADDET no.71, 1998). Compilation of performance data at the site is on-going.

A summary of the published grid-connected systems in the UK is shown in Table 2.7:

System	PV array size (kWp)	Inverter (kW)	Capital (US$)	Type
Vale residence	2.16	816	25,500	pergola
NPAC @ NU	39.5	494	681,700	facade
AMREL @ LU	2.16	741	35,700	non-BiPV
WHF	2.64	498	51,000	office roof
Oxford House	4.08	823	27,400	residential roof
Southampton U.	3.40	765	-	non-BiPV
Homerton Grove	1.62	741	-	roof tile
CAT	13.5	711	369,920	building roof

Table 2.7: Summary of UK grid-connected PV systems (Simmons, 1995). It shows that the UK has a cumulative grid-connected PV installation of 69 kWp.

2.4 Cost of BiPV power

It has been generally accepted that, for BiPV technology to become economically attractive for building applications, the module cost has to be about US$ 1 per Wp. At present, the module cost ranges from about US$ 3 to 16 per Wp. A selected list of costs cited in the open literature is shown in Table 2.8:

Publication	US$ per Wp	US$ per kWh	Comments
Archer, 1996	3.4 - 5.1	0.85 - 1.70	mix
Crick *et.al.,* 1995	8.3	0.79	sunshade
Cross, 1994	10.6	-	building
David, 1996	4.5	0.17 - 0.20	building
EREN-DOE, 1998	6.5 - 13.0	0.22 - 0.44	mix
EUDG XVII, 1995	7.0	0.61	general
Keller and Affolter, 1995	6.0	1.10	general
Markvart, 1994	10.0	-	rooftop
Open University, 1994	5.0	0.39	domestic
Pearsall, 1995	7.0	0.60	general
McNelis *et.al.,* 1996	3.8	0.72	facade
McNelis *et.al.*, 1996	-	0.60	rooftop
McNelis *et.al.*, 1996	-	1.16	cladding
PVPOWER, 1997	4.1 - 5.5	-	mix
Roaf, 1994	9.4	0.44	rooftop
Schmid, 1994	4.9	0.73	central
Sick and Erge, 1996	5.0	0.95	grid-connected
Strong and Scheller, 1993	14.0 - 22.0	-	stand-alone
Strong and Scheller, 1993	9.0 - 16.0	-	grid integrated
Taylor, 1990	3.4	0.31	mix
Wind and Sun, 1997	8 - 12	0.2- 1.0	mix
Average	7.74	0.65	-

Table 2.8: Sample costs of PV energy generation.

Table 2.8 shows several versions of PV cost estimates. It can seen that the average cost of a PV module (excluding central plants) is about US$ 7.74 per Wp and the average cost of PV energy generation is about US$ 0.65 per kWh. Thus this is about 4.7 times as much as the present electricity generation cost in the UK which is at US$ 0.136 per kWh. A typical economic estimate for a 100 kWp BiPV system costs is shown in Table 2.9:

Material	Cost in US$ per Wp
PV modules	4.8
Inverter	0.6
Cabling	1.2
Planning	1.2
Total	7.8
Maintenance	1 % of total

Table 2.9: Economic listing of PV system (Schmid, 1994).

Table 2.9 shows that the PV cost dominates the system and makes up about 60 % of the complete system cost, while the BOS cost takes up about 40 % of the total cost. This was corroborated by other publications (Sick and Erge, 1996). A summary of the typical comparative range of costs for BiPV technology for facades and other types of cladding and roofing materials is shown in Table 2.10:

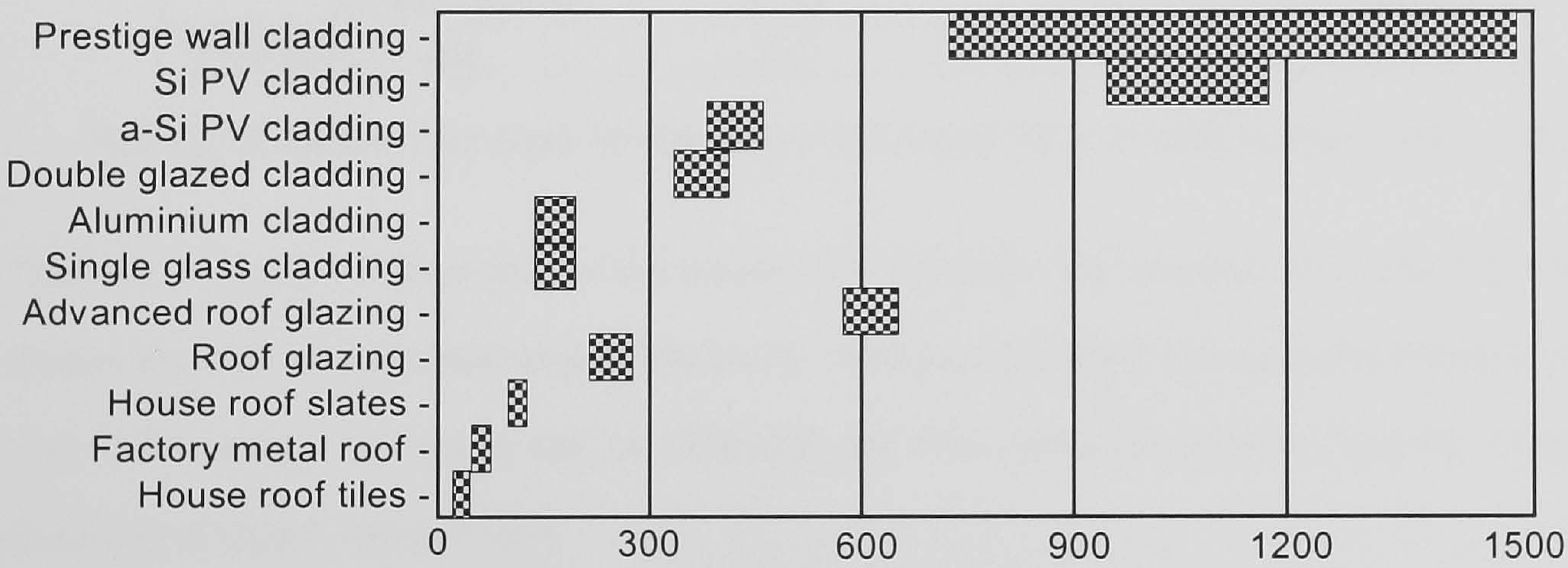


Table 2.10: Range of costs of the various PV facades and roof materials in US$ per m^2 (Leppanen and Spiers, 1997). a-Si - amorphous silicon.

Table 2.10 shows the comparative range of costs of building material. From here, it can be seen that the use of BiPV technology is still quite costly for Si cells and is comparable to a prestige wall cladding. However, the costs in using amorphous silicon (a-Si) very nearly matches that of double glazing. Besides costs, other major issues regarding to BiPV use that need to be addressed include:

- Architectural aspects (e.g. construction, aesthetics, operation and maintenance).
- Scientific and engineering aspects (e.g. shading, temperatures of the PV, wiring).

For the UK, an assessment made for an average non-domestic building, assuming a requirement of about 240 $kWhm^{-2}$ of plan area, the cost of electricity from building mounted PV systems after deductions of area-related costs and avoided roofing costs is shown in Table 2.11:

Non-domestic building	UK average (US$ per kWh)	UK best (US$ per kWh)
Present scenario	0.31	0.24
Illustrative scenario	0.15	0.14
Best scenario	0.09	0.07

Table 2.11: Cost of electricity from building integrated PV in the UK (Taylor, 1990).

The costs for a central power PV generation based on 1989 figures is shown in Table 2.12:

Component	Present (US$ per Wp)	Illustrative (US$ per Wp)	Best future (US$ per Wp)
PV module	3.0	1.3	0.5
Total BOS cost:	3.5	2.0	1.5
- (area related)	(2.9)	(1.5)	(1.3)
- (power related)	(0.6)	(0.5)	(0.5)
Total system cost	6.5	3.3	2.0

Table 2.12: Scenario of costs for UK PV central power plant in US$ per Wp (Taylor, 1990).

Tables 2.11 and 2.12 show that in the present UK scenario, the average PV costs are more than double the cost of conventional grid electricity. However, the best UK scenario predicted that the cost of PV energy can go as low as US$ 0.09 per kWh, which is cheaper than the present grid electricity of US$ 0.136 per kWh.

2.5 Conclusions

Based on the preceding discussions, general conclusions with regards to PV and BiPV technology can be drawn as follows:

- The knowledge in PV itself is well established and its use for power applications has been accepted in most nations world-wide, numbering into the many thousands.
- BiPV is a relatively new technology and the earliest practical systems have been installed as recently as in the 1980's.
- The technology can now be seen to be at the later stages of demonstrations and at an earlier stage of mass implementation. Certain countries are beginning to accept BiPV technology by

implementing short to medium term, large scale programmes. This shows a political acceptance amongst the governments in those nations.

- Literature on BiPV technology has been mainly in the forms of general concepts, overview and demonstration examples.
- The popular BiPV technology applications have been for walls and facades, roofs and large coverings, light filtration and screening elements.
- The basic scientific and practical engineering aspects of BiPV technology have been overcome, as shown in the demonstration examples. Residual technical issues regarding its optimised use in buildings are shading and thermal aspects of the modules.
- There have been a limited number of specialised literature on BiPV technology as an integrated system with evaluations of their synergistic benefits in the open publications.
- The economics of BiPV technology and energy generation are still at the helm of discussions. PV costs average at US$ 7.74 per Wp and generation costs average at US$ 0.65 per kWh.
- The pace of BiPV technology and applications in the UK has been slower than that of other leading nations due to the lack of a strong support from the government, despite having a strong technical capacity. This can be seen by having only eight publicised and documented UK grid-connected PV systems, with only five of the systems as being truly BiPV installations.
- In the UK, BiPV technology has often been seen as befitting the more prestigious buildings as well as for sunnier climate countries.
- Practical experience in BiPV technology within the UK has been very limited. At the time of writing, performance data from only two, out of the eight grid-connected systems are available. Others are either not being monitored or are still under-going analysis.
- There has been no published experience of BiPV technology, grid-connected or grid-interactive in the developing nations of the world, despite having half of the PV powered applications in the world installed in these nations.

Chapter 3. Overview of Malaysian Energy and Photovoltaics Applications

3.1 Malaysian energy overview

In light of the national aspiration towards industrialisation, it becomes apparent that a cursory monitor on energy trends be maintained for Malaysia. This has long been recognised and complete packs of energy balance sheets for Malaysia are available since the late seventies (Malaysian Energy Balance, 1993). The need becomes natural as the urgency for rapid industrialisation of any country, entails issues concerning the adequate supply of energy to power the wheels of industrialisation. However for Malaysia, this energy database has been traditionally maintained for fossil-based energy resources. The same tradition has not been established for renewable energy resources. On the other hand, its use has been clearly stated in the country master plans for development (Seventh Malaysia Plan, 1995). Upon considering these imbalances, it seems imperative to appreciate some of Malaysia's background as a nation in the context of energy scenario such as its geography and climate, population background, energy supply, policy and their relation to photovoltaic applications.

3.1.1 Geography and climate

Malaysia comprises of fourteen states, of which twelve are located in the Malay Peninsula and two are located along the northern coastline of the island of Borneo. The country spans from longitude of about 100 to 120 ^{o}E and latitude from about 1 to 6 ^{o}N. It is eight hours ahead relative to GMT. The approximate total land area is about 330,000 km^{-2} with about 60 % of the total land area covered by natural and plantation forests. Due to its location on the globe, its climate is considered to be hot and humid, typical of equatorial types. The weather phenomena experienced in Malaysia are the tropical cyclones, monsoon seasons, haze and thunderstorms (Malaysian Meteorological

Office, 1997). The principal meteorological (met) office, a Class 1, is located at the Sultan Abdul Aziz Shah International Airport, near the capital city of Kuala Lumpur.

The mean daily temperature for Malaysia is about 27 °C with diurnal variations of about 5 to 7 °C, and a Relative Humidity (RH) of about 70 to 90 % throughout the year. The windspeed average is about 0.4 ms^{-1}. The average daily global irradiation in Malaysia ranges from 4 to 6 $kWhm^{-2}d^{-1}$ p.a., of which about 30 to 50 % are diffused (Yatim, 1993; Sopian and Othman, 1992). This means that the use of PV technology in Malaysia seems to offer a very suitable option. Sample data for the various sites in Malaysian towns is shown in Tables 3.1 and 3.2:

Town	Ele.(m)	J	F	M	A	M	J	J	A	S	O	N	D	Ave
Alor Setar	46	6.5	7.0	7.0	7.0	6.1	5.7	5.7	5.6	5.5	5.7	5.6	5.6	6.1
C.Highland	1689	5.0	5.9	5.8	6.0	5.5	5.6	5.4	5.3	5.3	5.0	4.8	4.6	5.3
Ipoh	39	6.0	6.6	6.5	6.5	6.0	5.7	5.9	5.7	5.8	5.7	5.5	5.4	5.9
Kota Bharu	5	5.4	5.9	6.6	6.9	6.1	5.6	5.7	5.8	5.9	5.4	4.0	4.0	5.6
K. Lumpur	17	4.9	5.3	5.4	5.2	4.9	4.7	4.8	4.8	4.8	5.1	4.3	4.7	4.9
K.Tr'gnu	35	4.9	5.7	6.5	6.8	6.1	5.7	5.6	5.6	6.0	5.5	3.9	3.8	5.5
Kuantan	15	4.6	5.4	5.9	6.0	5.7	5.4	5.5	5.4	5.8	5.2	3.9	3.6	5.2
Melaka	8	5.5	5.8	6.0	6.0	5.5	5.3	5.2	5.4	5.3	5.3	5.0	4.8	5.4
Mersing	5	5.0	5.8	6.2	6.1	5.6	5.4	5.2	5.3	5.4	5.3	4.9	4.3	5.4
Penang	3	6.8	6.7	6.8	6.8	6.0	5.8	5.9	5.6	5.4	5.6	5.7	5.8	6.1
Senai	38	5.7	5.3	5.9	5.7	5.2	4.9	5.0	5.1	5.1	5.0	4.5	4.7	5.2
Sitiawan	8	5.8	6.5	6.4	6.5	6.1	6.0	5.8	5.7	5.7	5.4	5.4	5.3	5.9

Table 3.1: Daily average solar irradiation in units of $kWhm^{-2}d^{-1}$ from a fifteen year record for Malaysia (University of Massachusetts, 1987).

Month	Irradiation ($kWhm^{-2}d^{-1}$)	Temperature (°C)	Windspeed (ms^{-1})
Jan	5.1	26.9	0.3
Feb	5.6	27.3	0.3
Mar	5.8	27.5	0.3
Apr	5.8	27.4	0.3
May	5.3	28.4	0.3
Jun	5.1	27.5	0.3
Jul	5.1	26.7	0.3
Aug	5.1	27.2	0.4
Sep	5.1	27.0	0.5
Oct	5.0	26.8	0.4
Nov	4.5	26.3	0.4
Dec	4.4	26.9	0.3
Average	5.2	27.2	0.4

Table 3.2: Malaysian met data for monthly averages (Malaysian met office, 1995).

Table 3.1 shows the Malaysian met data obtained from a fifteen year record from twelve met stations throughout the country. The monthly averages show a daily solar irradiation value ranging from about 5 to 6 kWhm^{-2} with a yearly average of about 5.5 kWhm^{-2}. The total available solar irradiation as obtained from the met office shown in Table 3.2 indicates that the Malaysian met data for 1995 has a yearly average of 5.2 kWhm^{-2}, which is quite near to the fifteen year average. The hourly average values shown for the Malaysian met data in 1995 are graphically illustrated in Figure 3.1:

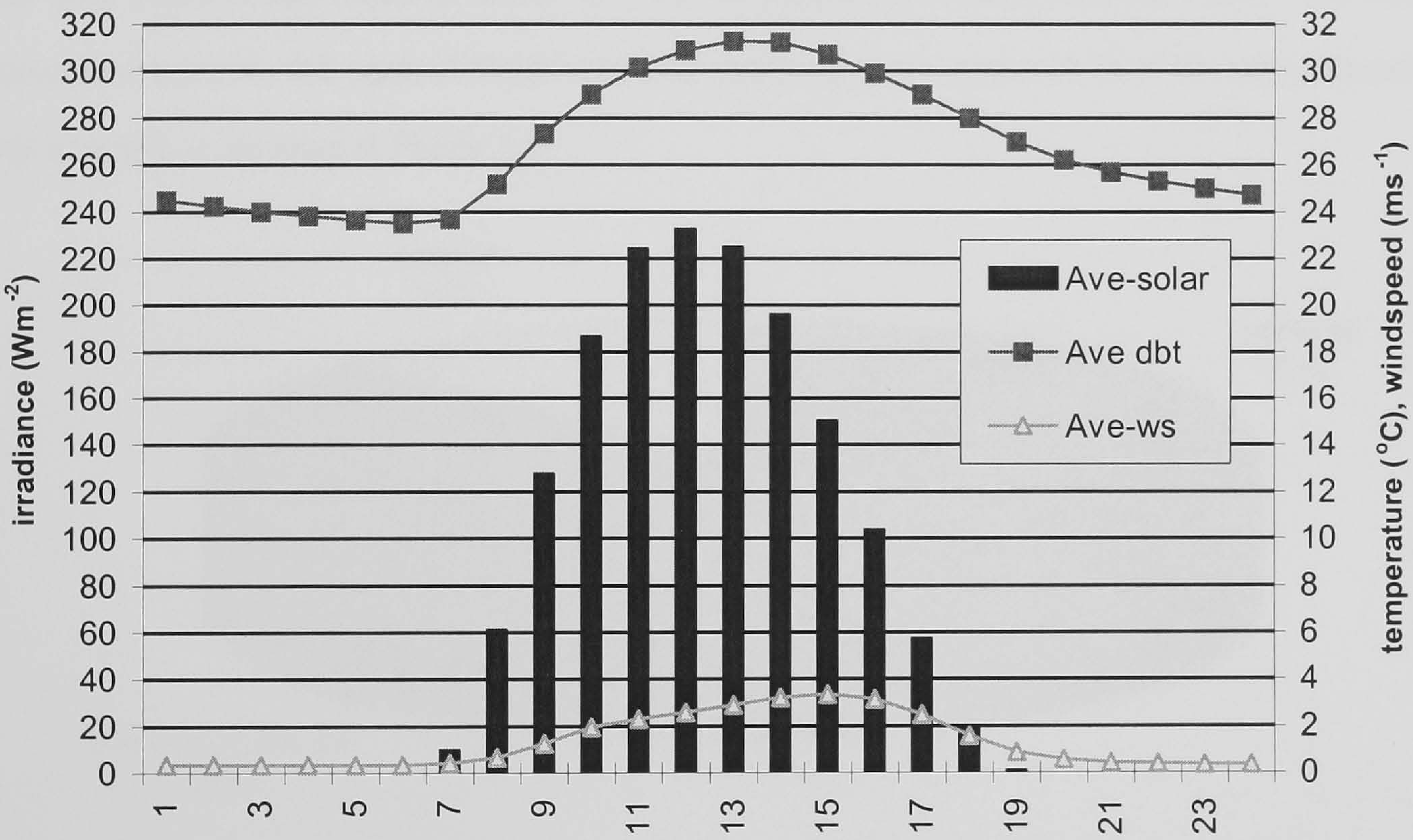


Figure 3.1: Mean hourly met data for Malaysia p.a. (Malaysian met office, 1995).

3.1.2 Population background

The population of Malaysia in 1995 was estimated to be 20 million people with an annual growth rate of about 2.0 % (United Nations, 1998), comprising of three major ethnic groups namely Malays, Chinese and Indians. The Gross Domestic Product (GDP) per capita for Malaysia in 1990 was US$ 2,700 (Yatim, 1993) and rose to about US$ 3,700 per capita in 1994 (AEEMTRC, 1994) In 1990, the total number of registered households were 3,614,600 at 4.98 persons per household. A total of 1,182,700 households were in urban areas while 2,431,900 households were in rural areas (Jaafar, 1993). This means that about 33 % of the population resides in urban areas while 67 % resides in the rural areas. However, this pattern is constantly changing as the rate of change of population in the urban areas was estimated at 3.35 % p.a. and that for the rural areas was estimated at 0.40 % p.a. (United Nations, 1998). This simply indicates that the Malaysian population is becoming more urbanised. If most of the households live in dwellings that are exposed to the sun, it can be contemplated that the potential for BiPV applications in Malaysia is vast.

Young Malaysians under the age of fifteen years make up about 37 % of the population while those over sixty years of age make up about 13 % of the population (United Nations, 1998). This makes Malaysians between the ages of fifteen and sixty years comprise about 50 % of the total population. This scenario is depicted in Figure 3.2:

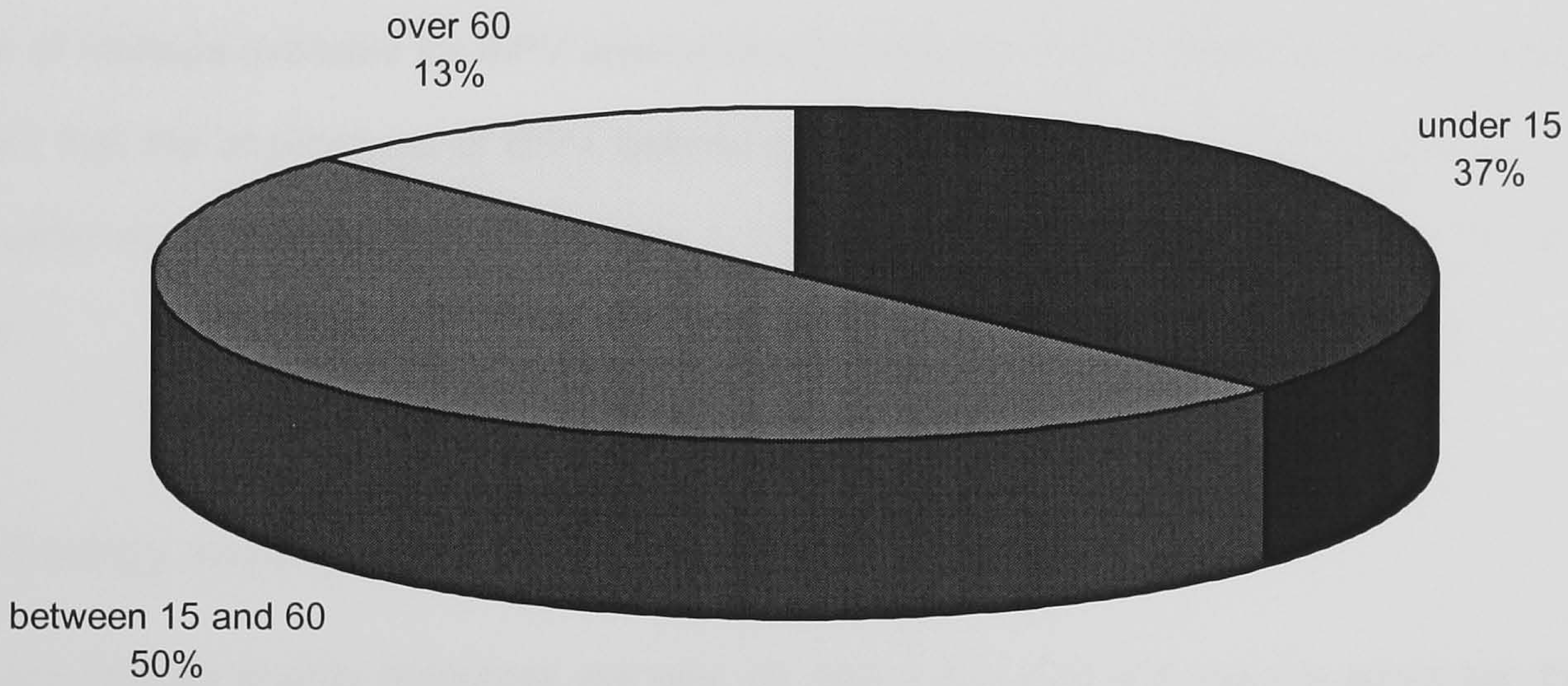


Figure 3.2: Estimated population make-up of Malaysians by age group in years in 1995 with a total population of 20 million (United Nations, 1998).

The statutory schooling age of Malaysians is between seven through to seventeen years of age. This makes the average population of Malaysians to be at a younger age, with a big portion within the schooling age. The schooling system is based on the British primary and secondary school systems with several amendments catered for within the requirements of the "National Education Philosophy" (Ministry of Education, 1997). The statistics regarding schools in Malaysia is shown in Table 3.3:

	Number of Schools	Pupils	Teachers	Number of Classes
Primary - male		1470774	58970	
Primary - female		1399893	91711	
Primary - total	7084	2870667	150681	86569
Secondary - male		883649	39619	
Secondary - female		910866	56905	
Secondary - total	1538	1794515	96523	50661
Grand total	8622	4665182	247205	137230

Table 3.3: Summary of student population statistics for Malaysia (Ministry of Education, 1997).

Table 3.3 shows that the total number of pupils in Malaysian schools make up about 23 % of the total population. The total number of head count that is involved directly in education, comprising of pupils and teachers only, adds up to about 25 % of the total population. Thus with 8,622 total number of schools, coupled with 3,614,600 households in the country, accumulate to a large number of rooftops available for BiPV applications in Malaysia. From these information, it becomes apparent that the applications of BiPV technology in Malaysian schools and residences not only offer readily accessible roofs but also have a vast potential influence on the young minds of the country.

3.1.3 Energy supply

Malaysia's primary energy resources are gas, oil, hydro and coal and exports about two thirds of her energy resources annually (Malaysian Energy Balance, 1993; Nor, 1992). The supply of primary commercial energy was estimated at 13.1 % p.a. (Seventh Malaysian Plan, 1997). However, the average Malaysian is a relatively small consumer of energy with about 1,500 kWh per capita p.a. (AEEMTRC, 1994). The energy supply and demand scenario by sector in Malaysia are shown in Tables 3.4 and 3.5:

Resource	Estimate	Production
Oil	2.94 billion bbl	622,470 bbl per day
Gas	56.90 TSCF	1,377,000,000 CF per day
Hydro (power)	29,000 MW	1,421 MW
Hydro (output)	123,000 GWh	6,363 GWh
Coal	771.4 million tonnes	410,000 tons per day

Table 3.4: Estimated recoverable supply of resources 1990 (Nor, 1992; Tamang *et.al.*, 1993).

Sector	Amount in GJ	% share
Industrial	250,000	44.6
Transport	230,000	41.1
Residential/commercial	70,000	12.4
Others (non energy)	10,000	1.8
Total	560,000	100.0

Table 3.5: Final energy use by sector in 1990 (Malaysian Energy Balance, 1992).

Table 3.4 shows that the recoverable energy supplies in Malaysia would seem modest. According to conservative estimates, Malaysia has been projected to maintain her status as "a net energy producing country" up to about fifteen years into the future (Ramatha, 1992). Table 3.5 shows that the bulk of energy expenditure was for industrial uses. Residential uses was 12.4 % of the total share. The cumulative power generation capacity was 5,242 MW in 1990, 7,241 MW in 1994, 11,427 MW in 1995 and by the year 2000, it was estimated to be about 15,493 MW (Seventh Malaysia Plan, 1997). The average rate of increase through 1995 to 2000 has been estimated to be about 12.8 % p.a. (Seventh Malaysia Plan, 1995). By the year 2020, it was estimated that the electricity demand would be at about 30,000 MW (Omar, 1994; Buletin Tenaga, 1992c). The figure for the year 2000 is about double that of 1994 and by the year 2020, it is about quadruple the 1994 capacity. This simply means that the electrical energy needs by Malaysia is on the steep increase. Traditionally the government has been supplying electrical energy through three boards, but as a consequence of its privatisation policies, this has been changing. At present, the major utility companies generating electricity in 1994 are shown in Table 3.6:

Company	Demand / Capacity (MW)	Customers ('000)
Tenaga Nasional Berhad Com.	5200 / 6900	3,500
Sabah Electricity Board Com.	280 / 450	190
Sarawak Electric Supply Com.	250 / 520	200
YTL Power Com.	1170	-
Genting Sanyen Com.	720	-
Sikap Power Com.	1300	-
Powertek Com.	440	-
Port Dickson Power Com.	440	-
Teknologi Tenaga Com.	600	-
Total	5730 /12540	3,800

Table 3.6: Summary of the present status of Malaysian electricity producers by demand and capacity sizes (Omar and Chon, 1994a and 1994b).

3.1.4 Energy policy

Basically, the Malaysian energy policy, still in effect, can be summarised as follows (Seventh Malaysia Plan, 1995):

- Diversification of energy mix to maintain self-sufficiency.
- Reduce dependence on oil as well as optimisation of the country's indigenous resources.
- Increase efficiency in the use of energy through fuel substitution and energy conservation.
- Encouragement of the private sector investment in the development of energy resources.

The aims are to:

- Introduce the use of coal, hydro and natural gas as primary energy sources besides oil.
- Ensure adequate energy supply by reducing dependence on oil and by developing and utilising alternative sources of energy.
- Promote and encourage the efficient use of energy and discharge of wasteful and non-productive patterns of consumption.
- Minimise environmental degradation in realising the above goals.

The implementation strategies to achieve these policies and aims include:

- A national depletion policy to control exploitation rates (effective since 1980).
- Use of unleaded petrol and natural gas for vehicles (effective since 1990).
- A national energy efficiency programme to increase awareness in efficiency (since 1991).
- A national petroleum policy to control prices.
- Encouragement of competition amongst power producers.
- Environmental impact assessment for all new energy projects.

The structure for decisional and implementation of energy related issues in Malaysia is shown in Figure 3.3 and a brief description of their roles are shown in Table 3.7:

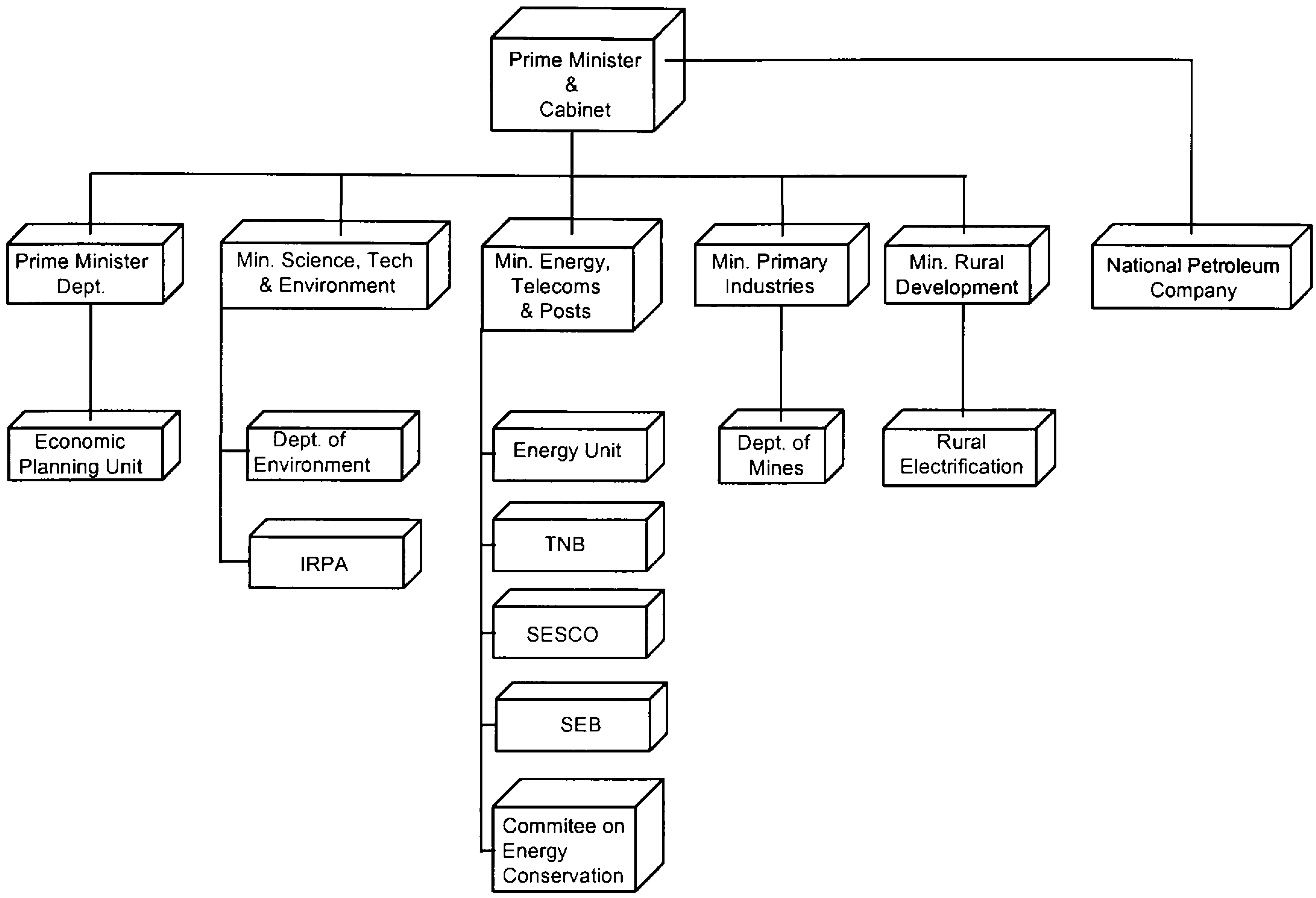


Figure 3.3: Hierarchy of the related agencies involved in energy within the government. The ultimate authority rests upon the cabinet committee on energy in the Parliament. TNB, SESCO, SEB are all government-owned utility companies. IRPA - Intensified Research in Priority Areas, which is a government funding platform for R&D activities which includes energy research.

Department/Agency	Role
Ministry of Energy, Telecoms and Posts, (METP)	implementation of policy, co-ordinating supply and pricing
Ministry of Domestic Trade, (MDT)	pricing of retail petroleum products
Ministry of Science, Technology and Environment, (MSTE)	research and promotion of renewable energies
Energy Planning and co-ordination Unit, (EPU)	strategic planning of resources and economics
Ministry of Rural Development, (MORD)	rural electrification
National Petroleum Company, (PETRONAS)	development and promotion of petroleum and gas

Table 3.7: Role of departments involving energy in Malaysia.

Figure 3.3 and Table 3.7 depict the government's organisational structure and each Ministry's role in relation to energy matters. However, the ultimate decision making body actually rests on the "Cabinet Committee on Energy". The government has also recently announced the establishment of an "Energy Research Centre" to co-ordinate R&D activities taken throughout the country and an "Energy University" (Malaysian Budget, 1998).

3.1.4.1 Policy on renewable energy resources

The government recognises the potential for solar, wind, wave and biomass energy resources. The utilisation of these sources grew at about 7.4 % p.a. from 92.5 PJ in 1990 to 132.3 PJ in 1995 (Seventh Malaysia Plan, 1995). The government also plans to implement thirty-two projects to generate electricity from solar technologies for 800 rural households in Sabah and Sarawak in this developmental plan. In terms of a policy statement on renewable energy resources, the government "encouraged its use however, without incentives" (Jaafar, 1993; Yatim, 1992; Ramatha, 1992). It has been reported that "these renewable potentials are virtually untapped and are classified as low priority in Malaysia" (Jaafar, 1993; Yatim, 1992). At the time of writing, solar thermal technology for domestic hot water systems appear to be the most widespread in use. Sales of Domestic Hot Water (DHW) systems in 1990 amounted to 4,000 units within the base prices of US$ 800 to 1,500 per unit which were manufactured locally (Zechariah, 1992). The first solar electric car was brought into Malaysia as a demonstration vehicle in 1998 (Berita Harian On-Line, 1998).

3.1.5 Electrification programme

The government plans to electrify most of the country though its "Rural Electrification" programme. This has been placed under the authority of the Ministry of Rural Development (MORD). As noted earlier, Malaysia has a substantial percentage of rural households. In 1990 the state of rural electrification reached about 91 %, 48 % and 52 % in Peninsula Malaysia, Sabah and Sarawak respectively, with a total national average of about 80 % (Seventh Malaysia Plan, 1995; Jaafar, 1993). The target is to achieve electrification at 100 % for the Peninsula, 75 %, for Sarawak and 80 % for Sabah, giving a national total of about 93 % by the year 2000 (Seventh Malaysia Plan, 1995). Of a total expenditure of US$ 18 billion for energy development programmes over a period of five years, about 60 % of this has been allocated for the development of electricity programmes (Seventh Malaysia Plan, 1995). The government has identified problems mainly due to logistics and communications and has set specific targets for its rural electrification programmes. This expenditure will serve to power up other development programmes, such as in the small and medium scale industries and the development of rural industries. Most of these industries have been scheduled to depend on commercial fuels such as electricity from the grid, petroleum products and biomass resources (Jaafar, 1993).

3.2 Malaysian photovoltaics applications

3.2.1 Existing applications

The applications of PV technology in Malaysia so far has been exclusively for stand-alone systems only. The use of PV for residential power has been popular in remote areas where the cost of grid-connection is uneconomic. Estimates of the total PV use as of 1994 for Malaysia was between 715 to 960 kWp with an estimated rise of about 10 % p.a. (Dalimin, 1997; Arshad *et.al.*, 1995; Buletin Tenaga, 1992a, 1992b, 1992c). The first use of PV technology in Malaysia was in 1976 for the supply of remote power for beacons. Since 1985, the Standards and Industrial Research Institute of Malaysia (SIRIM) has implemented eleven pilot solar PV projects for lighting and water pumping in Malaysia (Arshad *et.al.*, 1995). In May 1990, PV for lighting purposes in Sarawak on the island of Borneo was introduced. This was commissioned by a Belgian company with a peak capacity of 37 kWp for providing residential power to 200 inhabitants in two long houses in rural Sarawak. The cost of the whole system was US$ 220,000 (Buletin Tenaga, 1992b). This particular application gave a cost of US$ 5.9 per Wp. This application was justified simply because of demographic and economic reasons and the remoteness of the area. The next biggest project since then is in Papar, Sabah which has a 10 kWp Si-mono crystalline solar cells in 192 modules. It provides 240 volt to 30 houses for 24 hour domestic uses, under the authority of the Sabah Electricity Board (Dalimin, 1993). The applications of PV in the country can be broadly divided into the categories as follows:

- Governmental authorities.
- Manufacturing and services.
- Others (R&D).

3.2.1.1 Governmental authorities

The governmental authorities' use of PV technology can be summarised into four categories, namely: a) remote residential b) telemetry c) navigational and d) others. The governmental users of PV technology include: the METP, governmental research centres such as SIRIM, the Malaysian Agriculture Development Institute (MARDI), the Rubber Research Institute (RRI), the Department of Water and Canals, the Fire Board, the state Maritime Department of Sarawak and the Ministry of Rural Development (MORD). The total capacity installed has been estimated to be between 117.8 to 210.8 kWp (Arshad *et.al.*, 1995).

The most active user in the residential sector has been the MORD for its rural electrification programme. It has installed more than two hundred units of stand-alone PV systems (including hybrid systems) on islands off the coast of Peninsula Malaysia to provide rural power for residential use. The popular loads for these pilot island projects were for electric power for eight hours per house with three lighting and two power points with a total load of 100 Wp. The typical costs for this type of load with three PV modules and complete BOS system were about US$ 2,700 which gives a cost of about US$ 27 per Wp. The users benefited from the projects have been clinics, shophouses, police stations, mosques, schools and for street lighting. A much more significant PV project with a capacity of 10 kWp is for the island of Papar for residential use off the coast of Sabah in Borneo, which was installed in 1993. This MORD project was financed by the New Energy and Development Organisation (NEDO) of Japan and a follow-up project of an 80 kWp system has been proposed. The major suppliers of technology for the MORD projects has been BP Solar and Siemens-Showa Solar.

The next biggest use by the government was for navigational aids. It was felt that the market for this type of uses has been saturated for Peninsula Malaysia, but demands have been increasing in Sabah and Sarawak. The technology has been supplied from Neste, Arco and Solar Volts with modules ranging from 4 Wp to 40 Wp.

3.2.1.2 Manufacturing and services industries

In this category, the major commercial scale users of PV technology has been the Malaysian Railway Company (KTM) and Telecoms Malaysia Company (STM). Other users, mostly non-governmental telecommunications companies were at the stages of experimentation and pilot projects. Another major application of PV technology has been proposed for the Highway Incorporated in Malaysia (PLUS) as it embarks on a project to light up the major East-West highway crossing through the mountain range in Peninsula Malaysia. The popular applications of PV technology for STM has been power for its repeater stations. A site experience in the installation and commissioning of a remote power diesel-battery-PV hybrid power system was included in this research programme (Shaari, 1995). The KTM has been using PV power for level crossings. As of 1994, the total installed capacity from these two users of PV technology has been estimated at 139.4 kWp (Arshad *et.al.*, 1995).

3.2.1.3 Others (R&D)

The major users of PV modules in this category engulfs the academic institutions in the country. However, these are relatively insignificant users. At the time of writing, there are eight public universities and institutions of higher learning in the country. With regards to PV R&D, only two of these institutions have active involvement in this area and one is in the beginning stages. The groups are from the Universiti Kebangsaan Malaysia - UKM (Othman, 1994), the Universiti Malaysia Sabah - UMS (Dalimin, 1997) and the Universiti Sains Malaysia - USM (Ibrahim, 1995). The PV related work at UKM involved PV materials and fabrication, applications for water pumping and applications for powering remote highway cameras. The work at USM involved basic testing measurements, basic calculations of energy from PV and material studies for multi-junction solar cells. The work at UMS involved stand-alone PV applications for remote village power.

A summary of the major PV applications in Malaysia is shown in Table 3.8:

Type of application	Total kWp installed	% installed	US$ per Wp
Rural telecoms	320	33	-
Residential electrification	155	16	5.9 - 27
Repeater stations	125.4	13	16
Oil platform (navigational)	80	8	19
Navigational aids	30.7	3	-
Electric fencing	30	3	-
Microwave transporter	30	3	19
Telemetry	24.6	3	-
Water pumping	9	1	19
Street lighting	7	< 1	27
Lighthouse	2	< 1	-
Aviation warning	2	< 1	40
Billboard	0.92	< 1	25
Others	139.9	15	-
Total	956.52	100	23*

Table 3.8: Estimation of installed PV applications in Malaysia up to 1994. (Dalimin 1997, Arshad *et.al.,* 1995). * average value.

As shown in Table 3.8, the largest user of PV technology was for rural telecommunications with 33 % share of the total installed capacity. This is followed by rural electrification at 16 % and then for repeater stations at 13 %. These three major applications amounted to about 62 % of the total share in Malaysia. However, with the government's plans for higher percentage of rural electrification, the residential PV portion is expected to increase. This seems to offer the option of using BiPV technology in these rural areas via stand-alone, hybrid or localised grid-interactive power systems. Actual detailed figures are not available, but the cost of PV for these systems averaged at about US$ 23 per Wp. This is much higher than the reported US$ 3 to 10 per Wp in the open literatures. However, the Malaysian figure is closer to that quoted by established publication for stand-alone systems at about US$ 14 to 22 per Wp (Strong and Scheller, 1993). Also, it must be noted that these applications have been for remote areas only and costs for using other types of power would have been higher in the longer run.

3.2.1.4 PV product suppliers and contractors

There have been four major companies in Malaysia that were involved in the business of selling, installing and commissioning of PV technology, namely: Bestium Corporation, Renewable Energy Systems, PROJASS Energy and Telecommunications and BP Solar. Shell Solar no longer has its operations in Malaysia. The major suppliers of PV technology for PROJASS has been BP Solar while Siemens has been the major supplier for the other two local companies. The closest Japanese-based PV module manufacturer was HEXON in Singapore but is no longer in operation. The actual complete scenario on the activities of these companies on the applications of PV technology in Malaysia was very difficult to get. However, an estimate of the annual turnover of these companies are shown in Table 3.9:

Company	Annual turnover (million US$)	% share
BP Solar	0.8	15
Renewable Energy Systems	0.8 - 1.5	22
Bestium	0.8	15
PROJASS	2.5	48
Total	4.9 - 5.6	100

Table 3.9: Annual turnover of PV product suppliers and contractors (Arshad *et.al.*, 1995).

The costs quoted in Table 3.9 for the installation of packaged PV technologies for the following companies were:

- Bestium @ US$ 19 per Watt.
- PROJASS @ US$ 6 per Watt.
- Renewable Energy Systems @ US$ 38 per Watt.
- Average @ US 21 per Wp.

It comes as no surprise that the company, PROJASS has a big portion of the market in Malaysia. The popular periods of warranty normally offered has been ten years on the modules, and from three to five years on the batteries.

3.2.1.5 Observations on the use of PV technology in Malaysia

It has been observed that there were many issues faced in the applications of PV technology in Malaysia. The main issues were:

Economical

The technology costs were high, probably to over-pricing. Most of the PV systems lacked open market drive and were funded by the government and corporate bodies which were able to absorb the high initial costs. The commercial private market seemed to need end-financing schemes to make the application more acceptable.

Organisational

The works related to PV technologies and applications lacked co-ordination and understanding amongst the groups or individuals working on them. Government departments seemed to be competing at who had better technologies rather than sharing lessons that had been learnt from each others' experience. The co-ordination amongst the R&D groups amongst the local universities showed better dissemination of knowledge but rivalry amongst individuals were persistent.

Technical

There seemed to be a lack of trained manpower in specialised areas in PV. There were only a few persons in the whole country that actually had on-site experience in the designing and installing such systems and the number of expert personnel capable of commissioning such installations was even less.

Education

The public at large was uninformed about the benefits of PV technology. As a consequence, there was a lack of awareness, priority and urgency in environmental issues from the masses, as well as the implementation bodies within the country.

3.2.2 BiPV and related technologies literature review

Limited literature is available with regards to PV technology applications and related activities in Malaysia. Most publications discussed and reviewed renewable energy technologies generally. A limited number presented very basic experimental and testing work in PV application areas for stand-alone applications (Dalimin, 1997; Ibrahim, 1995; Othman, 1994; MdZain, 1992; Dalimin, 1987; Dalimin *et.al.*, 1987). Only one publication presented a systematic PV applications survey in Malaysia (Arshad *et.al.,* 1995), while others mentioned in-passing (Buletin Tenaga, 1992a, 1992b, 1992c). A few authors related supervision work on the setting up of a PV powered highway camera (Othman, 1995). All of these PV technologies have been for remote, non building-integrated power systems. Despite the fact that these stand-alone systems are established, there have been no publications presented that describe or discuss the performances of any of these systems.

Basically Malaysian literature and expert experience on BiPV technology at the time of writing were non-existent (Jaafar, 1995).

Other related activities published in Malaysia presented work in solar radiation issues (Sopian and Othman, 1992) and solar architecture work (Zain-Ahmed *et.al.,* 1991). There were several publications related to thermal comfort studies in Malaysian buildings (Zain-Ahmed *et.al.,* 1997, Abdulrahman and Kannan, 1997 and 1996; Abdulshukor and Young, 1993; Hanafi *et.al.*, 1991, Inangda, 1990). It was found that the comfort air temperature for Malaysians averaged at 28.2 ^{o}C with a clo value = 0.55, MET value = 1.0, Relative Humidity (RH) = 50 %, wind velocity = 0.1 ms^{-1} and a Mean Radiant Temperature (MRT) = Dry Bulb Temperature (DBT) (Abdulshukor and Young, 1993). This temperature average is higher than the ASHRAE publication as well as the recommended Malaysian comfort temperature in conditioned buildings with DBT = 24 ^{o}C and RH = 60 % (Malaysian Energy Guideline, 1989). The range of DBT and RH in the comfort zone was between 25.5 to 29.5 ^{o}C and 45 to 90 % respectively (Abdulshukor and Young, 1993). A similar study found that the optimum conditions for comfort was attained in Malaysian conditioned buildings at a DBT of 26.3 ^{o}C, RH = 73 % and a wind velocity of 0.3 ms^{-1} (Zain-Ahmed *et.al.*, 1997). Another study found that the Malaysian low cost housing had an internal air temperature of between 24 to 27 ^{o}C in the daytime and 20 to 23 ^{o}C in the nightime (Hanafi *et.al.*, 1991). A study for naturally ventilated classrooms in Malaysia found by using regression techniques, that the comfort air temperature was 27.4 ^{o}C (Abdulrahman and Kannan, 1997). The measured air temperatures of several schools in Malaysia was found to have an average of about 27.98 °C (Inangda, 1990). Progress and studies on this issue are still on-going (Abdulrahman, 1998; Zain-Ahmed, 1998). It seems at the first instance that the comfort temperature for Malaysian students averaging at 28.2 °C can be met by the existing design of the standard Malaysian school as shown by a study of measured data (Inangda, 1990). These information with regards to the air temperatures within these naturally ventilated built forms in Malaysia serves to give an educated idea as to the kinds of temperatures, the PV modules will be experiencing when they are integrated into Malaysian buildings.

3.3 Conclusions

Based on the relevant literature survey for Malaysia generally, and a review of PV applications specifically, the following general conclusions can be drawn:

- The electrical power demands have been on the steep rise at about 13 % p.a. within the last decade.
- The government's policy on renewable energy technologies has been one of acceptance and recognition. However, there are no incentives for its use.
- The installed capacity for PV applications in Malaysia was between 715 to 960 kWp up to 1994. However, this use has been established for remote power systems only. It has been estimated that demands for PV power is increasing and its market is expanding at about 10 % p.a..
- There have been no publications on the performance of the existing stand-alone PV systems despite the significant numbers of installations. There exists few published work on PV research generally and most that did, regarded only very basic experimental and testing work.
- Issues in PV use have been mainly due to high initial costs at about US$ 23 per Wp, a lacking of expertise and education, with very few trained personnel in PV technologies.
- Grid-interactive or grid-connected BiPV technology and expert experience in Malaysia are non-existent. However, the potential applications for BiPV technology in Malaysia is vast, on rooftops of households and school buildings.

- BiPV technology application in Malaysia seems to offer a very technically viable option in view of its climate, prior acceptance of PV technology, electrification plan and the number of potential households available.

Chapter 4. PV System Operation and Cost of Generation

4.1 PV system operation

4.1.1 Electrical properties

The solar cell is basically made up of an n-type and a p-type semiconductor, buried in a specially-made encapsulation. As light strikes the front surface, an electromotive force is generated that can drive a Direct Current (DC) through an external circuit. The detailed physics and engineering aspects of this generation can be referred to several comprehensively-written publications (Lorenzo, 1994; Markvart, 1993; Treble, 1991; Overstraeten and Mertens, 1986; Twidell and Weir, 1986; Green, 1982; Wilson, 1979). A simple conceptual application of the solar cell is shown in Figure 4.1:

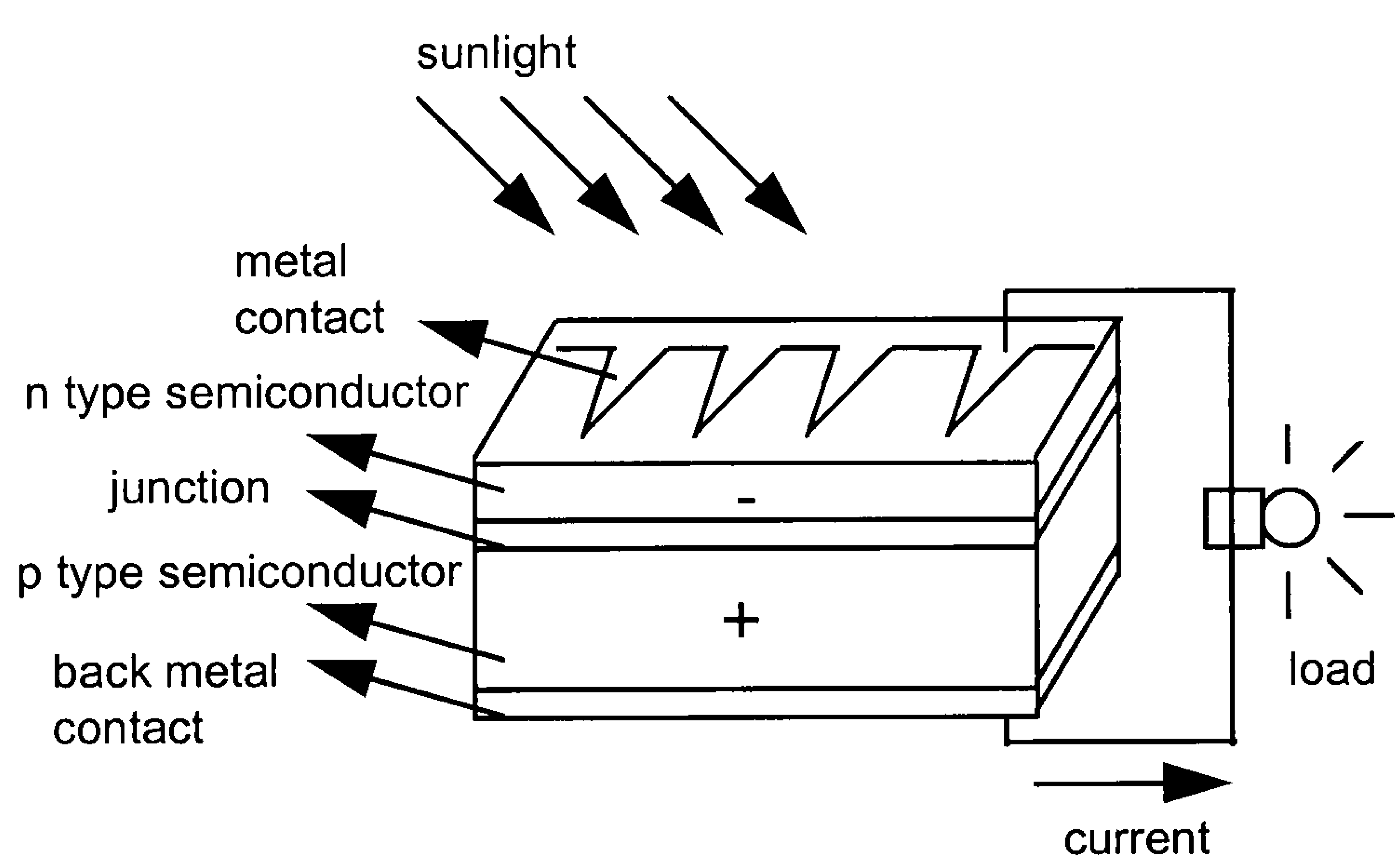


Figure 4.1: Conceptual application of a typical solar cell connection for powering a load. As sunlight strikes the solar cell, an electromotive force is created in the junction region. An external path enables the DC generated current to flow in a closed circuit through a load.

The solar cell can be most conveniently represented using an equivalent circuit diagram shown in Figure 4.2:

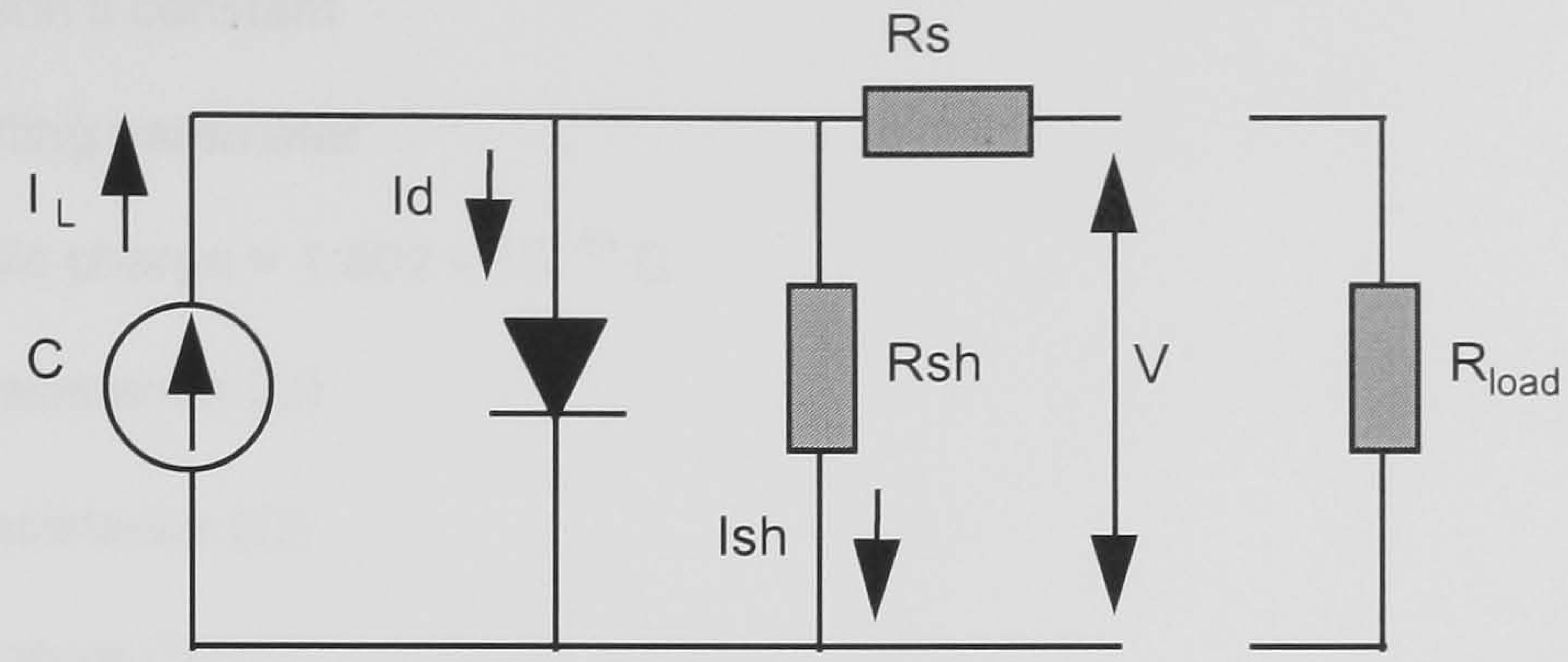


Figure 4.2: Equivalent circuit of a solar cell. The components are: C - the solar cell; I_L - photocurrent; Id - diode current; Ish - shunt current; Rsh - shunt resistor; Rs - series resistor; V - cell voltage.

The equivalent circuit diagram shown in Figure 4.2 can be mathematically described using the five parameter model, comprising of the i) photocurrent I_L, ii) the diode reverse saturation current Io, iii) the shunt current Ish, iv) the series resistance Rs and v) the shunt resistance Rsh. The equation giving the current I of the solar cell that summarises this model can be expressed as:

$$I = I_L - Id - Ish \qquad (A) \qquad 4.1$$

but $$Ish = \frac{V + IRs}{Rsh}$$

and by definition of the Shockley diode current $Id = Io \left\{ \exp\left[\frac{qV + IRs}{mkT}\right] - 1\right\}$

Thus, current of the cell can be rewritten as:

$$I = I_L - Io \left\{ \exp\left[\frac{(qV + IRs)}{mkT}\right] - 1\right\} - \left\{\frac{V + IRs}{Rsh}\right\} \qquad (A) \qquad 4.2$$

where

I_L - photocurrent (A)

Io - diode reverse saturation current (A)

Ish - shunt current (A)

k - Boltzmann's constant

m - curve fitting parameter

q - electronic charge = 1.602×10^{-19} C

Rs - series resistance (Ω)

Rsh - shunt resistance (Ω)

T - temperature (^{o}C)

V - voltage (V)

By setting I = 0 in Equation 4.2, we obtain by definition, the short circuit current of the cell Isc, which can be expressed as:

$$Isc = I_L = Io \left\{ \exp \left[\frac{(qV + IRs)}{mkT} \right] - 1 \right\} \qquad \text{(A)} \qquad 4.3$$

Rearranging Equation 4.3 for voltage gives, by definition the open circuit voltage Voc, which is expressed as:

$$Voc = \frac{mkT}{q} \ln \left(1 + \frac{Isc}{Io} \right) \qquad \text{(V)} \qquad 4.4$$

Thus the electrical power P, available from the solar cell can be expressed as:

$$P = I \times V \qquad \text{(W)} \qquad 4.5$$

where I = current (A) and V = voltage (V).

The characteristic current versus voltage (I-V) curve of a module is similar to that of a solar cell. A typical characteristic I-V curve for a PV module is shown in Figure 4.3:

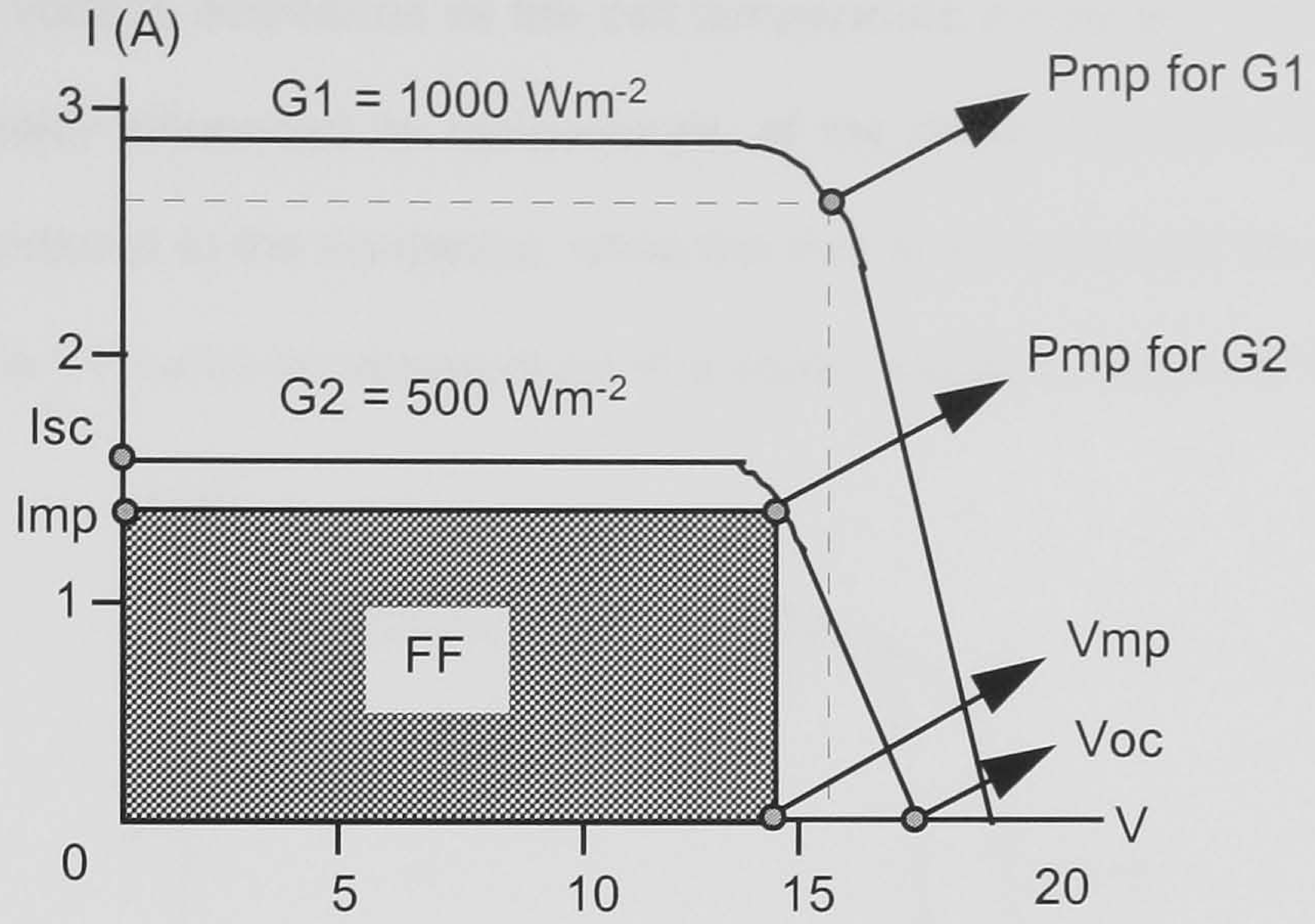


Figure 4.3: A typical I-V characteristic curve for a PV module. Also shown are the effects of two different irradiances G1, G2 on the module; Isc - short circuit current; Imp - current at maximum power; Voc - open circuit voltage; Vmp - voltage at maximum power; The shaded area marked FF is defined as the Fill Factor.

Figure 4.3 shows two levels of solar irradiances G1 and G2. At a solar irradiance level of G2, the maximum available power is shown by the shaded area under the I-V curve. This shaded area is defined as the Fill Factor (FF) and is expressed as:

$$FF = \frac{Pmp}{Isc \times Voc} = \frac{Imp \times Vmp}{Isc \times Voc} \qquad 4.6$$

where

Pmp - maximum power available from the module (W)

Imp - current at maximum power (A DC)

Vmp - voltage at maximum power (V DC)

FF - Fill Factor with typical values ranging from about 0.7 to 0.8

The voltage variation of the solar cell is influenced by temperature with a negative rate of coefficient, frequently expressed as:

$$\frac{dV}{dT} = -2.3 \ mV^{o}C^{-1} \qquad 4.7$$

This means that the voltage decreases as the cell temperature increases. The current output of the solar cell is only weakly influenced by temperature, of the order ~ 6 $uA^{o}C^{-1}cm^{-2}$. The Isc is often assumed to be proportional to the irradiance, while the Voc is a logarithmic function of the current. A typical variation of the I-V curve on temperature of a solar module is shown in Figure 4.4:

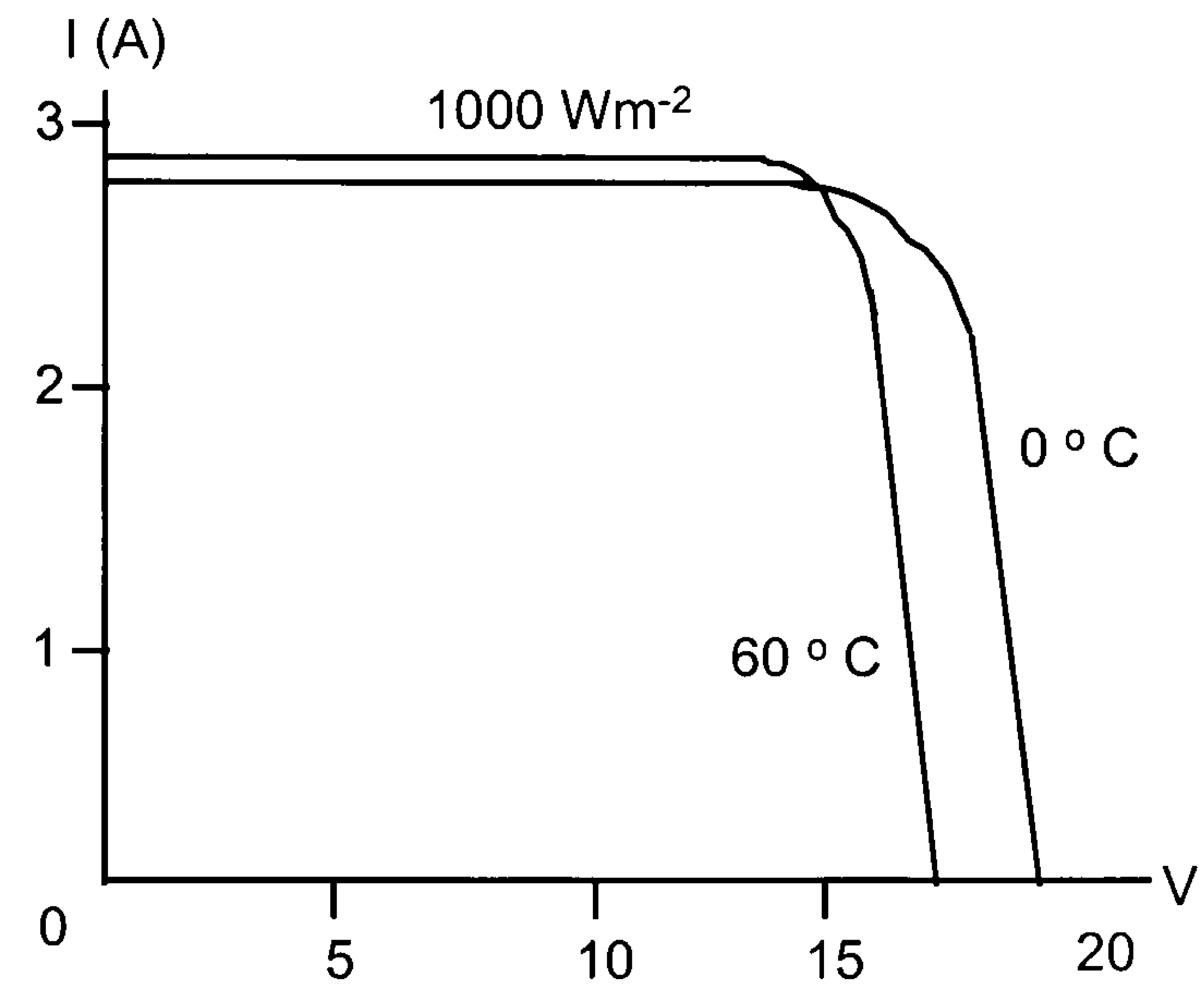


Figure 4.4: I-V curve variation of different temperatures of a PV module.

The conversion efficiency η, is calculated from the following equations:

$$\eta = \frac{\text{Poutput}}{\text{Pinput}} = \frac{\text{Vmp x Imp}}{\text{G x A}} \qquad 4.8$$

or

$$\eta = \frac{\text{Voc x Isc x FF}}{\text{G x A}} \qquad 4.9$$

where

A - area of PV panels (m^{-2})

FF - fill factor

G - irradiation on PV area (Whm^{-2})

Imp - current from PV at maximum power (A DC)

Vmp - voltage from PV at maximum power (V DC)

4.1.2 The PV module

An individual solar cell typically has an area of 100 cm^2 and produces an Isc of about 3.0 A and a Voc of about 0.5 V. This gives a typical power of about 1.5 Wp from each solar cell. Since many traditional stand-alone PV applications involve lead-acid batteries of 12 V, the solar cells are normally connected in series so as to produce a more suitable operating voltage comparable to the minimum requirement to charge the batteries. A typical module has 33 to 36 cells in series and generated an Isc of about 3.0 A and Voc of about 16 to 21 V. Usually a bypass diode is connected in parallel to each series linked cells as a protective measure against avalanche effects that might occur. The connection of solar cells in this way is called a "module". These modules are then encapsulated in special toughened materials with specific standards to ensure long lifetime. Commercial PV technology products are available in these basic modules and the modules have an estimated lifetime of 15 to 30 years of reasonably efficient operation life. The typical make-up arrangement for the solar cells in the literature is shown in Figure 4.5:

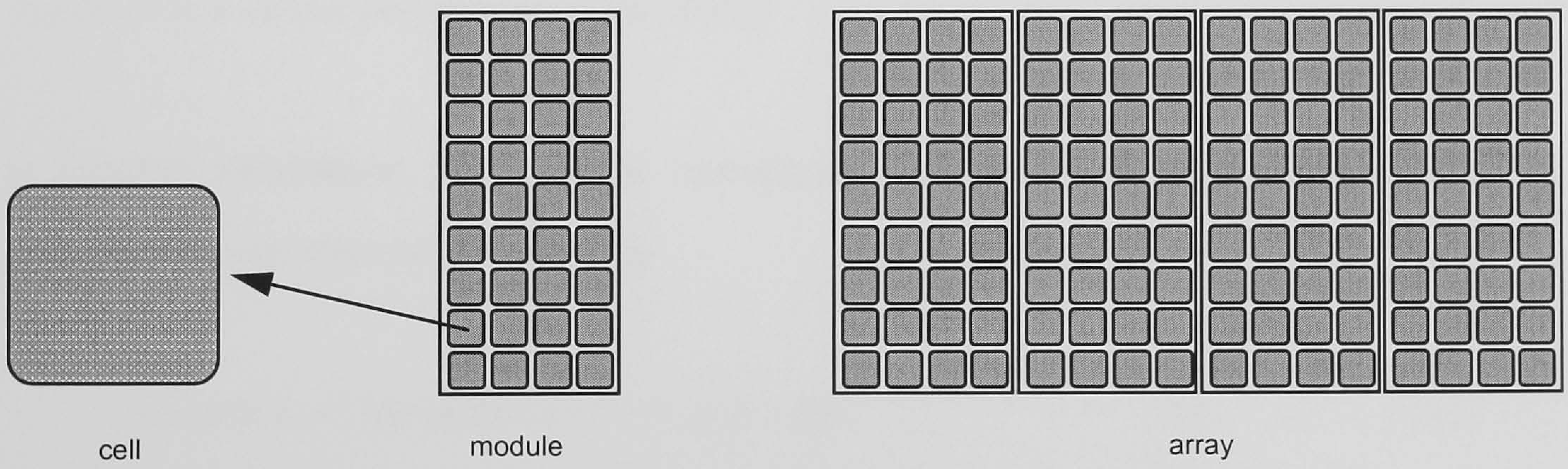


Figure 4.5: Typical make-up arrangement of the module and array.

The modules available commercially often cite characteristics under Standard Testing Conditions (STC). At these conditions, the Isc, Voc and Pmp are then measured. The STC is defined as:

Irradiance	1000 Wm^{-2} at normal incidence
Spectrum	Air Mass (AM) 1.5
Cell temperature	25 ^{o}C

The standard generating cell temperature is characterised by using the concept of Nominal Operating Cell Temperature (NOCT) which is defined as the cell temperature operating at:

- Irradiance = 0.8 kWm^{-2}
- AM = 1.5
- Ambient temperature = 20 ^{o}C
- Wind speed = 1 ms^{-1}

The value for the NOCT can be calculated using the following equation:

$$Tcell - Tamb = \frac{NOCT - 20}{0.8} \times G \qquad (^{o}C) \qquad 4.10$$

where

Tcell - cell temperature (^{o}C)

Tamb - ambient temperature (^{o}C)

G - irradiance (kWm^{-2})

Typical NOCT values vary between 42 to 45 (^{o}C).

In practical installations, the empirical relationships between temperature array and system performances can often be expressed as:

$$Isc\ (at\ T) = Isc\ (at\ 25\ C) \times [\,1 + b\,(T - 25)\,] \qquad (A) \qquad 4.11$$

$$Voc\ (at\ T) = Voc\ (at\ 25\ C) \times [\,1 - a\,(T - 25)\,] \qquad (V) \qquad 4.12$$

$$P\ (at\ T) = P(at\ 25\ C) \times [\,1 - c\,(T - 25)\,] \qquad (W) \qquad 4.13$$

where Isc is the short-circuit current, Voc is the open circuit voltage, P is the power, and:

T - array temperature (^{o}C)

a - curve fitting coefficient = $3.7 \times 10^{-3}\ ^{o}C^{-1}$

b - curve fitting coefficient = $6.4 \times 10^{-4}\ ^{o}C^{-1}$

c - curve fitting coefficient = $4.0 \times 10^{-3}\ ^{o}C^{-1}$

4.1.3 Types of system configurations

The technology is ever developing and new state-of-the-art technologies appear in the markets continuously. Newer modules with higher efficiencies, modern inverters with more modular systems (e.g. module inverter) and smart controllers are being researched, developed and manufactured. However, all working PV systems have certain basic systems configurations. Generally speaking, there are three main categories of PV systems which can all be building integrated, namely: a) stand-alone system, b) hybrid system and c) grid connected system. The conceptual block diagrams of the these main categories are shown in Figures 4.6a, 4.6b, 4.6c, 4.6d, 4.7, 4.8a and 4.8b respectively:

4.1.3.1 Stand-alone systems

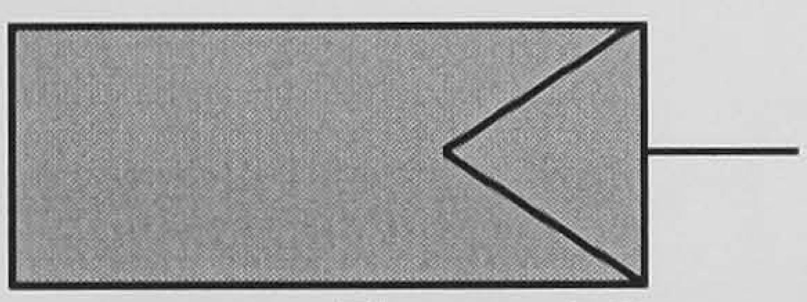


Figure 4.6a

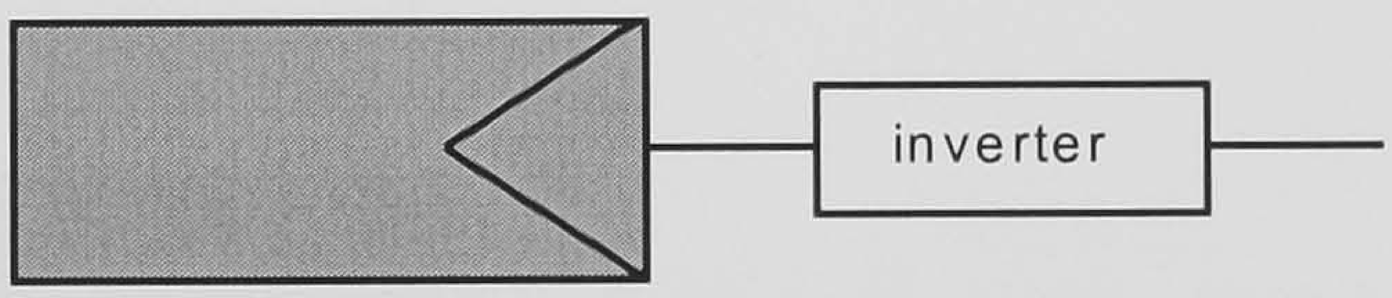


Figure 4.6b

Figure 4.6a: Stand-alone, DC without batteries - used for battery charging or water pumping.
Figure 4.6b: Stand-alone, AC without batteries - for normal/commercial AC uses.

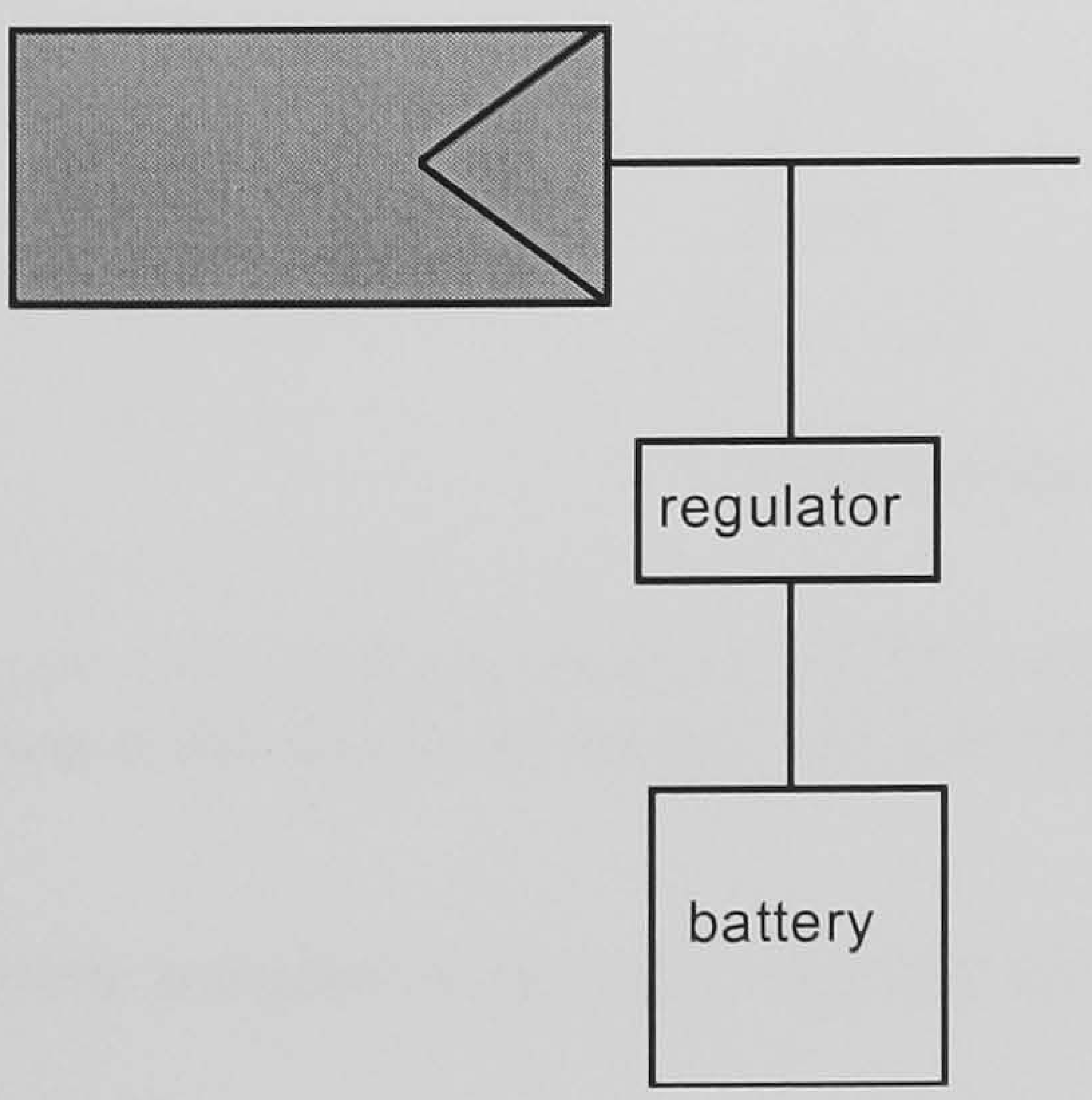


Figure 4.6c

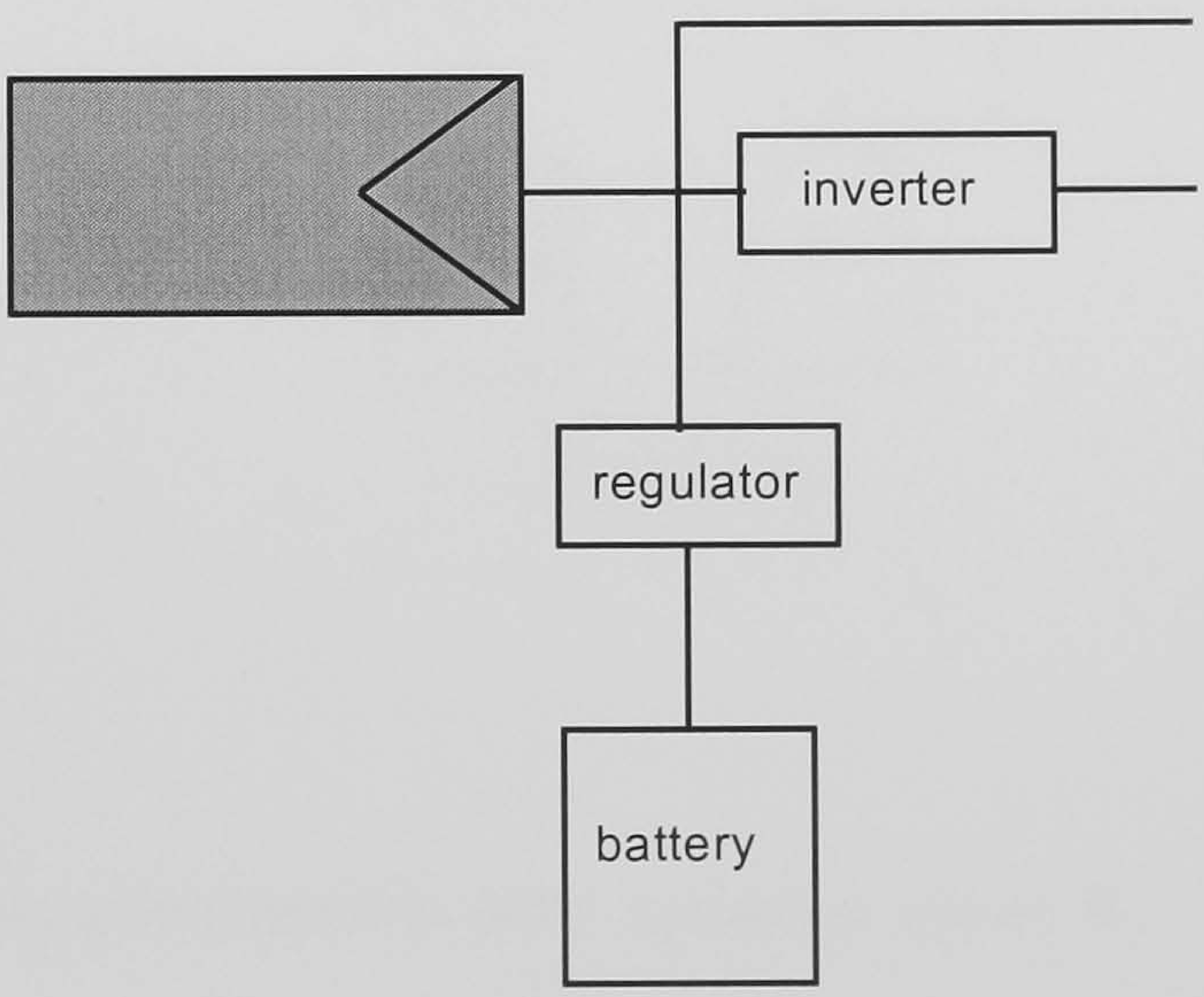


Figure 4.6d

Figure 4.6c: Stand-alone, DC with batteries - for telecoms, navigational aid, traffic control, lighting, TV, fridge.
Figure 4.6d: Stand-alone, AC/DC with battery - for domestic supplies in remote villages.

4.1.3.2 Hybrid system

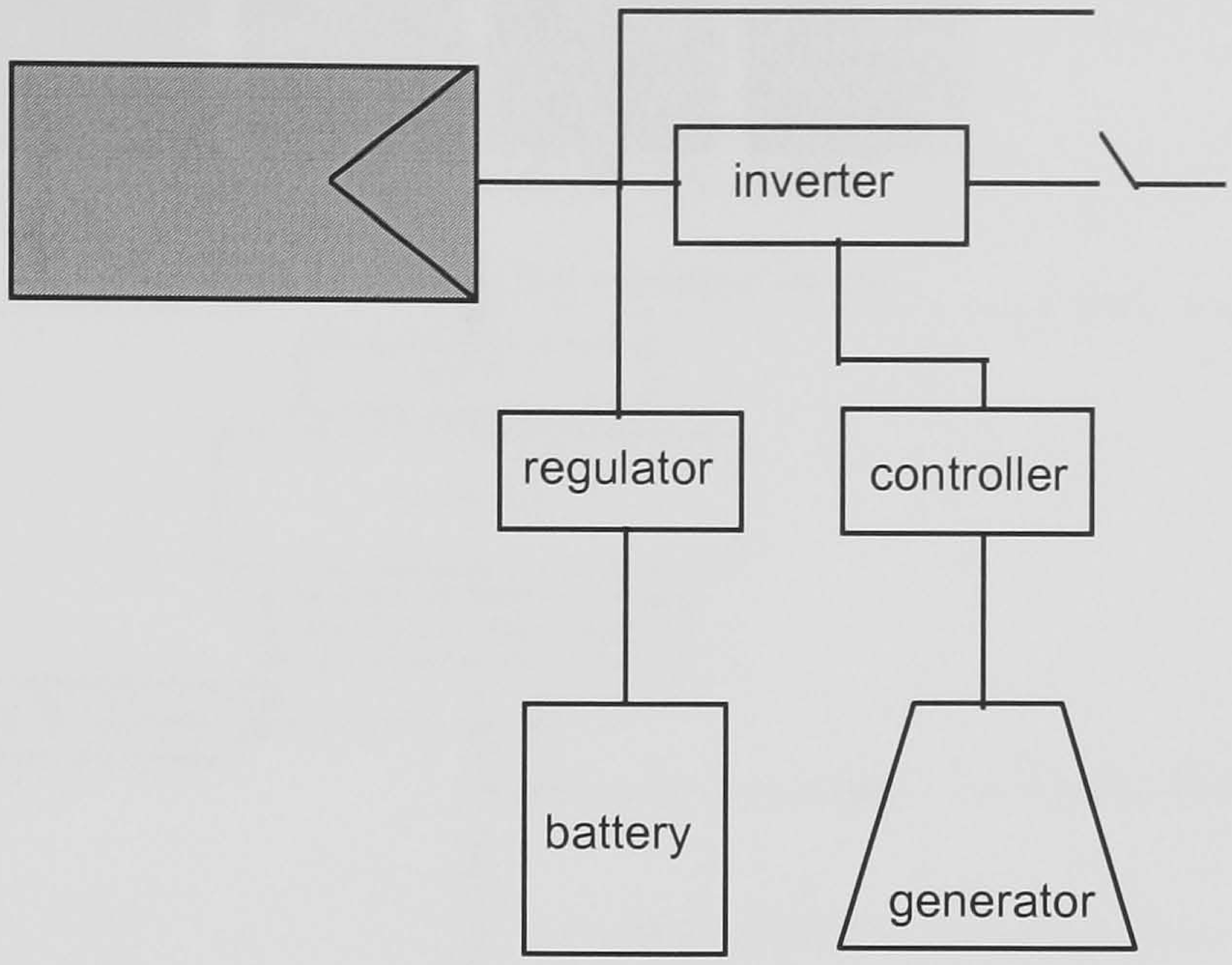


Figure 4.7: Hybrid system for a variety of applications (with battery back-up).

4.1.3.3 Grid-connected system

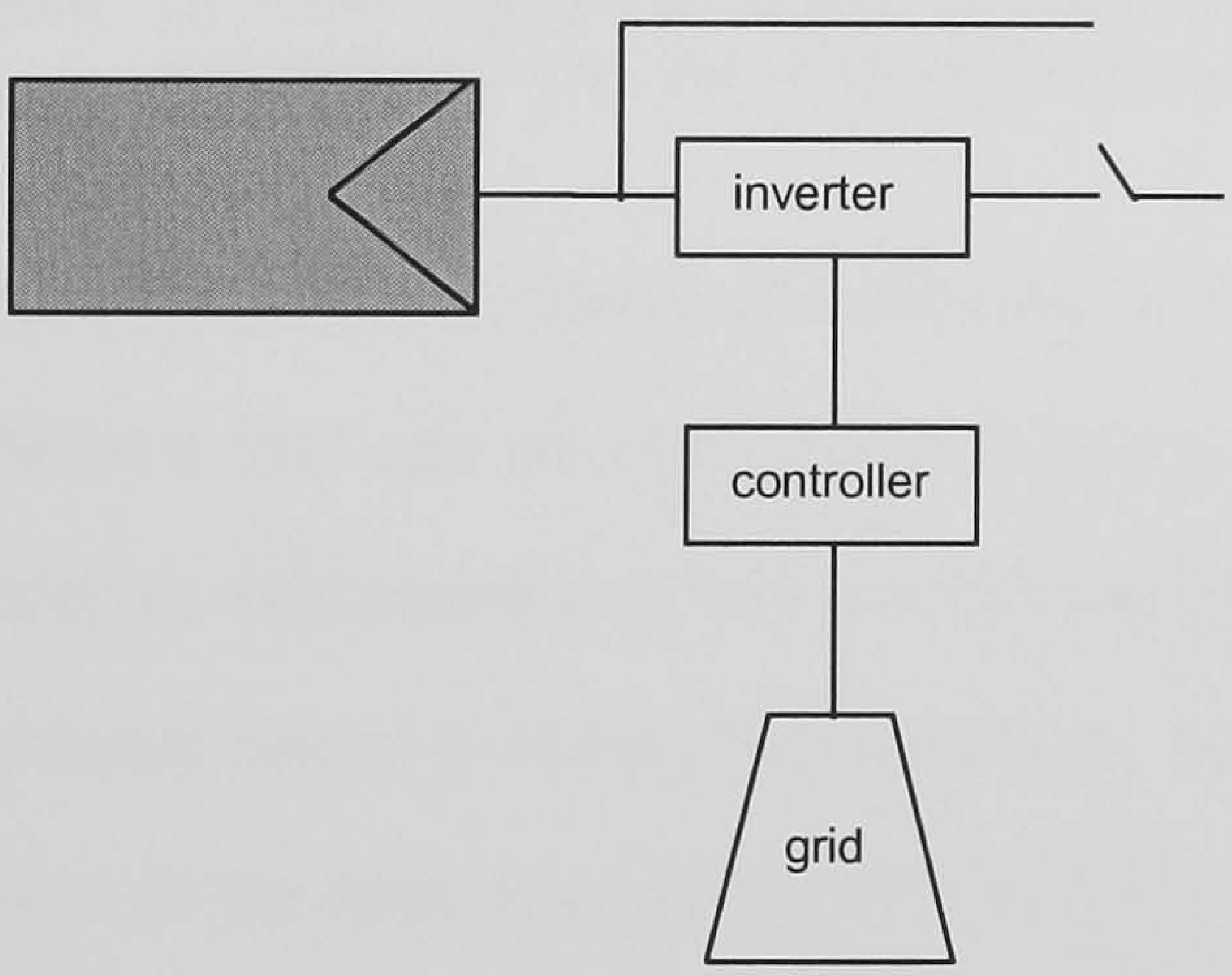


Figure 4.8a

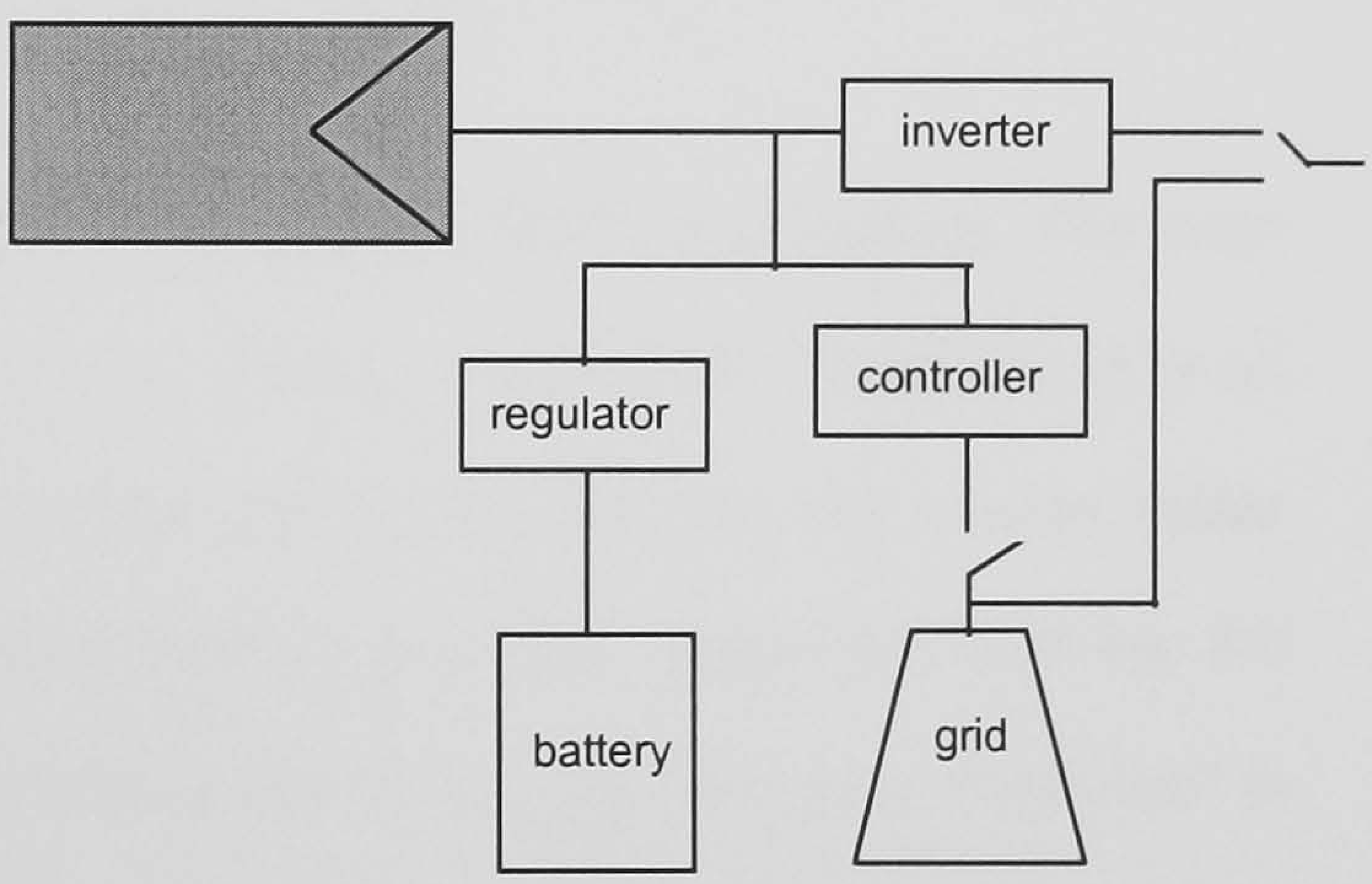


Figure 4.8b

Figure 4.8a: Grid-connected, AC/DC without battery.
Figure 4.8b: Grid-connected, AC with battery.

A more detailed schematic diagram of a typical working grid-interactive BiPV system is shown in Figure 4.9:

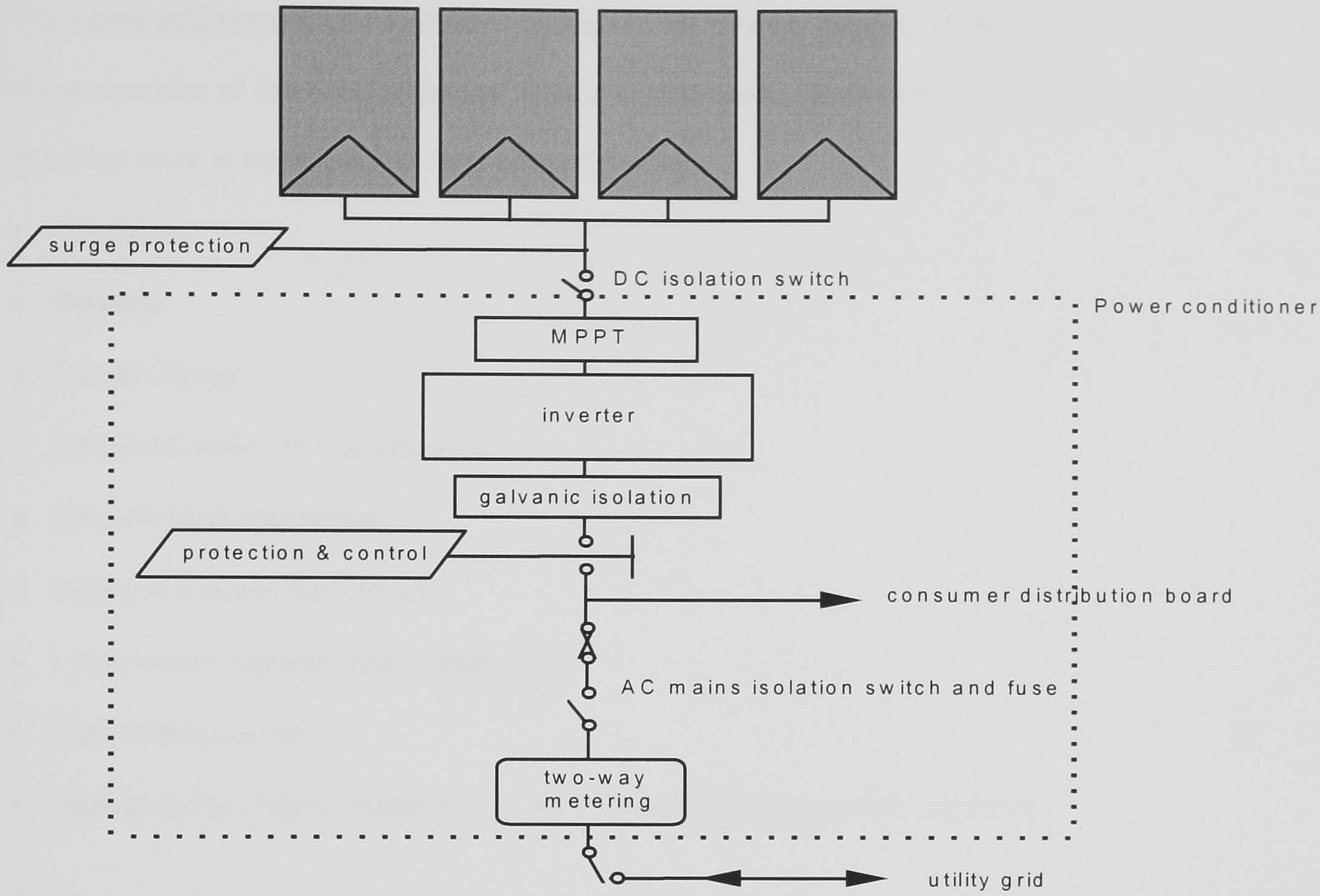


Figure 4.9 Flow diagram of a grid-connected BiPV system (PViB Pack, 1995). MPPT - Maximum Power Point Tracker. Galvanic isolation is a protection system.

Figure 4.9 shows a typical grid-interactive PV system, often used in BiPV applications. The main difference that can be seen is the dotted box termed as "Power Conditioner". Basically, it is an electronic equipment that is inserted between the normal distribution box and the energy meter commonly found in homes and buildings, with an input facility for energy generated from the PV arrays. In the case of a grid-connected BiPV system, the power conditioner acts as a "controller" in managing energy demands from the load, energy supply from the PV arrays and energy interactions between the PV-load-grid combination. The power conditioner is also equipped with a galvanic isolation protection system to safeguard repair works during grid shut-downs. Modern day inverters normally incorporate all of these equipments in a single housing thereby making it neater and easier to install.

The types and combinations of BiPV system to be chosen depend on the types of application and the economics of the circumstances. However, the basic requirements of a good BiPV system are that they have to have the following characteristics:

- Economic.
- Reliable.
- Proven design.
- Required minimum maintenance.
- Efficient load appliances.
- Safety of system from shock.
- Low electromagnetic (EM) disturbance.
- Easy maintenance.
- High security - high probability that the system will always satisfy the load.

4.1.4 Components of BiPV systems

The main components of a working PV system are:

4.1.4.1 DC-DC converters

This device are used to convert DC output from the PV array to suited DC voltage requirements. For many stand-alone systems, the bus-bar voltages are often designed as multiples of 12 V DC.

4.1.4.2 Maximum Power Point Tracker

The Maximum Power Point Tracker (MPPT) is a special converter to keep a PV generator operating at or near the maximum power point. It is a microprocessor that senses the voltage and current every ~ 30 ms and keeps on computing and adjusting the power output to be matched with the load for maximum power. Its purpose is to maintain an optimum value of power generated by the array during operation times.

4.1.4.3 DC-AC inverters

Most electrical appliances in the household use an Alternating Current (AC). Since the PV modules produce DC output, an inverter is needed to convert from DC to AC. For grid connection, the inverter must meet voltage, frequency and harmonic purity. Self commutated inverter are normally used in stand alone systems while line commutated inverters are normally used in grid interactive systems.

4.1.4.4 Power management and control

This is a device that automatically controls the flow of energy from the PV array or from the grid or other back up in accordance with the load demands and conditions of irradiation, temperature and state of charge of the batteries.

Modern inverters incorporate smart features that engulf DC-DC converters, MPPT, power management and control, and galvanic isolation protection systems (Halcrow Gilbert, 1993; Strong and Scheller, 1993).

4.1.5 Sizing procedure

Proper sizing is a very crucial step in the designing of PV and BiPV systems. Under-sizing of BiPV systems, especially for stand-alone applications, will drain its back-up systems and will prove to be expensive in the long run. Over-sizing of BiPV systems makes them unnecessarily expensive and will deter many prospective applications. For grid-connected BiPV systems, the more important aspects are financial and architectural constraints. In the current practise, the best option for BiPV technology is to use the power generated directly by the BiPV building itself.

The systems design and sizing are best done using computational programming softwares. However, each type of software normally abides by certain common and basic algorithms. The algorithms may range from the most fundamental and simplest forms, using the hand calculator, to the more complex, using powerful computational iterations. Several of the latter methods have been developed at an advanced stage and a number of relatively cheap BiPV computer models are commercially available in the market. These are discussed in detail in a later Chapter. However, certain basic elemental information are required. A summary of the design and sizing process is shown in Figure 4.10:

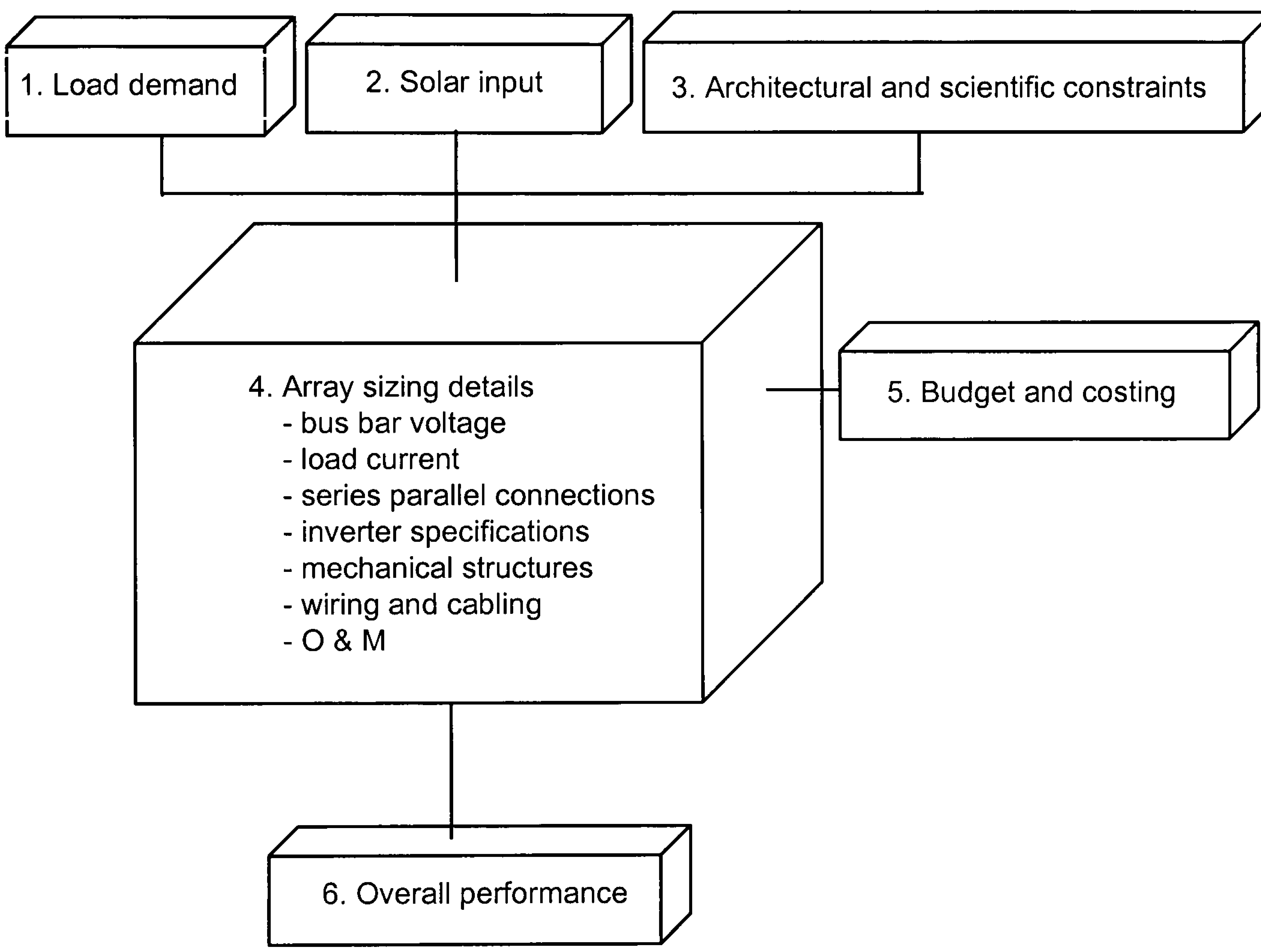


Figure 4.10: Summary of basic design and sizing algorithm for BiPV systems.

A discussion of the chart shown in Figure 4.10 is as follows:

1. Load demand - This is an estimate of the appliances ratings that are going to be used. This includes the ratings of the equipment as well as the approximate hours of use in a day. This part will actually dictate the size of the whole PV array and cabling that will be used in stand-alone PV systems.

2. Solar input - This is the environmental data for the site or closest site. Most solar radiation data available are given in the form of global horizontal irradiation. Thus estimates of the solar irradiation on the tilted panel at the geographical latitude must be made. Other data include ambient temperature and wind velocity. These data are used to quantify the amount of energy input into the BiPV system.
3. Architectural and scientific constraints - These simply mean that the building design needs to be considered for building integration of the PV modules. Orientation, layout and the landscape must be designed for BiPV applications in new buildings and must be considered in refurbishments. Scientific constraints cover the broad spectrum for PV and BiPV optimum operations, such as shading of panels, electrical safety and regulations, and maintenance.

4. Array sizing details - This algorithm includes issues such as:

- bus-bar voltage - this is the nominal voltage of the DC bus bar. For DC systems, this is normally the rating of the highest current, and voltage of the biggest load. For AC systems, this bus voltage should be compatible with the input voltage or window of the inverter.
- load current - based on the load demand, suitable cable sizes for each load must be determined for safety margins.
- Series parallel connections - this part includes the determination of the number of series-connected strings of PV modules needed to meet the minimum requirement of the load demand based on the available solar input. Comparisons of information from available energy, load demand and the I-V curve of the PV modules give the best answer for the calculations. For battery storage systems, the maximum allowable depth of discharge is decided at this point. For larger systems, the temperature effects must be considered.
- inverter specifications - at this point, a suitable inverter size can now be determined. However, this must be matched to the operating DC window and a suitable under-sizing of the inverter should be considered for optimum operations.
- mechanical structures - the types of structure for the PV panels must be considered carefully to ascertain safety regulations be met.
- wiring and cabling - suitable cable sizes leading from the array to the inverter must be used.

- O & M - design of BiPV systems must include considerations for operation, maintenance and safety checks.

5. Budget and costing - A match in design and costs should be within the requirement and purpose of the BiPV installation. Should the cost of a first sizing design be excessively high, the iterations in design needs to be reviewed.

6. Overall performance - Estimates of the overall performance of the designed system should be done. These include yields and efficiencies of the system. This will then enable calculations of the installed costs, PV costs and PV generated energy costs be determined. Also comparisons with other BiPV site performances can be done from the information obtained at this stage.

4.1.6 Performance indicators

The accurate performance indices for the PV system is best calculated on computer from monitored data obtained from a site for a considerable duration of time. Numerous computer model packages for performing these calculations are presently available in the market. The typical performance indices used for BiPV systems and their relationships are summarised as follows:

- Solar irradiation ($kWhm^{-2}d^{-1}$) - This is the daily solar irradiation value for a specific site that will be the energy input into the PV system. It forms the basis of all calculations regarding PV power systems.

- Total yield (kWh) - This is the actual amount of energy that is available as output from the complete system per annum (p.a.), depending on the peak capacity. For BiPV applications that require AC output, the energy appears from the inverter output in AC form.

- Final yield ($kWhkWp^{-1}$) - This is the ratio of the total yield (kWh) to the peak rating of the installed PV array (kWp) normally expressed p.a. It gives a normalised value of a particular system and thus provides a common base so that all different PV installations can be compared on like terms. Typical values for an installation in Southern Europe with a solar irradiation of about 4 $kWhm^{-2}$ per day normally gives a final yield of about 800 $kWhkWp^{-1}$ p.a. For Northern Europe with a solar irradiation of about 2 $kWhm^{-2}$, the final yield is normally around 500 $kWhkWp^{-1}$ p.a. The best systems with grid-connection with a PR of 80 % often gives a final yield ranging from 800 to 1400 $kWhkWp^{-1}$.

- Array yield ($kWhd^{-1}kWp^{-1}$) - This is the final yield divided by the number of days. Typical figures in Europe may range from about 1.3 to 3.7 $kWhd^{-1}kWp^{-1}$.

- Performance Ratio (PR) (%) - This is the overall performance indicator of the complete BiPV system. It takes into account all factors that affect the system performance and gives an overall convenient score by a particular system. It is calculated as the ratio of the final yield to the solar irradiation at Standard Testing Conditions (STC) of 1 kWm^{-2}. A PR score of below 60 % is often considered to be needing work and the best PV systems may reach a PR of up to 80 %.

4.2 Cost of generation

A fundamental economic index in energy matters is often the cost of energy generation. This is often expressed as cost per unit of energy generated. A simple formulation for this is expressed as follows (EUDG XVII, 1995; Treble, 1993):

$$\text{Electricity cost (US\$ per kWh)} = \frac{\text{System price + O\&M cost (US\$) / Peak rating (kWp)}}{\text{Final yield p.a. (kWhkWp}^{-1}\text{) x Payback period (years)}} \qquad 4.14$$

The number of years of energy savings to equal its initial investments is termed as the simple payback period. This is expressed as:

$$\text{Payback period (years)} = \frac{\text{Cost of investment (US\$)}}{\text{Cost of savings (US\$) p.a.}} \qquad 4.15$$

The use of a PV system typically requires a larger initial capital investment. This has been accepted in remote PV applications. For less remote applications, using the present state of technology and the conventional system of costing used, the payback period for the PV investment often exceeds the effective operational lifetime of the PV modules themselves. However, when the system operational lifetime is taken into consideration, it often becomes reasonable to use PV systems in the long run. As technology advances, along with increasing energy rates and environmental pressures, the cost structure of PV energy systems may then be in need of a revision.

Chapter 5. BiPV-UK: The WHF Office Building and Monitoring System Set-up

5.1 The Whittle Hill Farm office building

The Building integrated PhotoVoltaic UK (BiPV-UK) system studied in this research project was the Whittle Hill Farm (WHF) office building of Beacon Energy Ltd. in Leicestershire. It is the UK's first privately-owned office building that uses BiPV technology. The BiPV-WHF office installation is under the proprietorship of Professor Anthony Marmont. It used to be an old farm building that has been transformed by its new owner into a specially designed energy conscious BiPV-WHF installation. This was achieved by installing the building with PV technology and enhanced with a variety of energy efficient equipment. The equipment included a high efficiency condensing boiler, a gas fuelled generator set, remote-controllable roof blinds and a compactor waste disposal unit. The co-ordinates of the site is 52^{o} 43' North and 01^{o} 15' West of Greenwich Meridian. The main office complex has two large office rooms, a smaller-sized clerical office room, a medium sized conference room that could accommodate ten people seated, a coffee room, a utility room with freezer and a restroom. Adjoining buildings include a plant room, a large store, a smaller store and a covered parking lot for several cars. Within the courtyard, there is a small garden with water running from a higher pool to a lower one and is circulated by means of a variable speed pump. The walkway stretches the South-facing and West-facing perimeters of the building and is directly accessible from all the rooms. It stretches from the plant room at one end, to the utility room at the other end of the U-shaped building layout. The whole office is surrounded by undulating hills of green grass. Details of the design and construction are depicted in Table 5.1:

Date built	June 1995
Architect	Richard Watson and Partners
Landscape	David Shaw (Appleton Group)
BiPV roof	SOLAPAK Ltd. and Univ. Wales at Cardiff
Heating/cooling	John Knight
U-value	- floor 0.4
-	- wall 0.35 - 0.4
-	- roof 0.25 - 0.3
-	- door 1.5 - 2.5
Boiler	- 11.4 kW Lennox condensing
Waste disposal	- Lectrolav servolator

Table 5.1: Summary of BiPV construction of WHF.

A schematic 3D sketch of the office is shown in Figure 5.1:

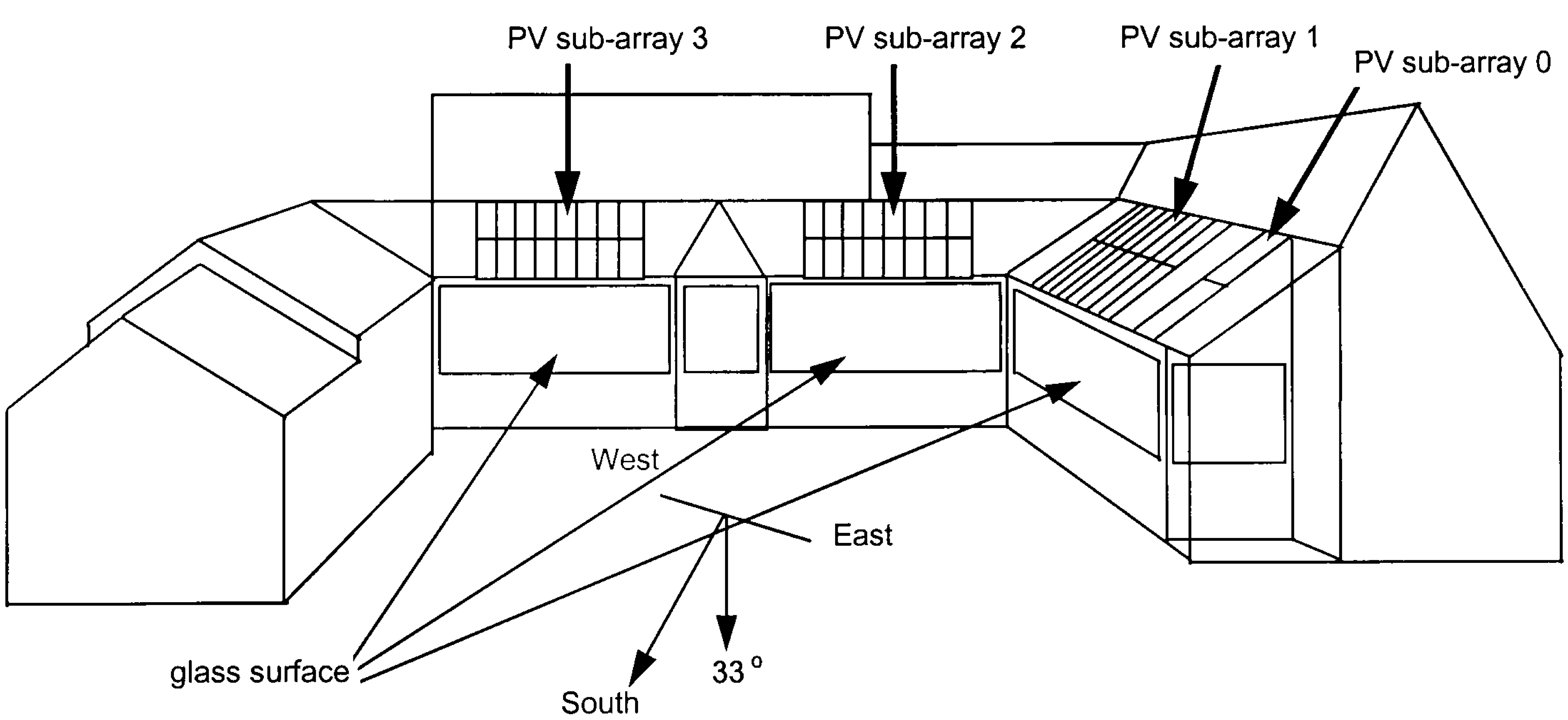


Figure 5.1: A 3-D sketch of the BiPV-WHF office building (not to scale). Gross area of PV modules integrated into the roof is about 21 m^2.

Photographs of the BiPV-WHF office buildings are shown in Photographs 5.1 and 5.2:

Photograph 5.1: View of the landscape at WHF site office.

Photograph 5.2: Front view of the main WHF office buildings.

5.1.1 The PV array

The PV array has been integrated as part of the roof of a walkway of the building. The PV modules are roof mounted, inclined at about 25 ° from the horizontal. The PV modules are flushed alongside glass roofing which had similar colour to the dark-blue monocrystalline modules. There are fifty Siemens M55 PV modules with a peak capacity of 2.75 kWp. The expected lifetime of these modules was twenty years. The wall of the walkway is made of transparent glass with a glass-to-wall ratio of approximately 60:40. One of the reasons for this design was to achieve an elevated air temperature for supply to the boiler in an adjacent plantroom. The internal side of the glass wall of the walkway was eventually covered with a horizontal Venetian type blind to provide control over the amount of daylighting entering the building. The PV system either exports or imports energy, to or from the grid via two separate meters, three phase combined, depending on the amount of solar irradiance available. The photovoltaic roof was designed by experts from the University of Wales, College at Cardiff, and installed by SOLAPAK Ltd., UK. The PV module specifications are shown in Table 5.2:

Manufacturer	Siemens	% uncertainty
Model	M55	-
Weight	5.5 kg	-
Number of modules	50	-
Open circuit voltage	17.4 V	-
Short circuit current	3.15 A	-
Power per module	55 Wp	± 5
Efficiency of module	12.4 %	-
Gross area of integrated PV modules on WHF roof	21 m^2	-

Table 5.2: PV module specifications at WHF.

The fifty modules are divided into four sub-arrays namely: sub-array PV0 consisting of two isolated non-connected modules, sub-array PV1 consisting of sixteen modules in series, sub-array PV2 consisting of sixteen modules in series also and sub-array PV3 consisting of sixteen modules in series as well. Sub array PV0 was mounted by the designer for monitoring purposes and therefore not being used for grid-interactive connection. Sub-arrays PV1, PV2 and PV3 are connected in parallel and have separate individual junction boxes which are mounted in enclosures placed on the backside of the modules and concealed by the ceiling of the walkway. This gives rise to only three live wires leaving the junction boxes, leading to the string combiner which is placed in the plant room. Thus each of the grid-connected sub-arrays PV1, PV2 and PV3 gives an output of 3.14 A DC and an array voltage of 278 V DC respectively. The total output leaving the PV arrays and entering the inverter then gives a current of 9.4 A DC and a voltage of 278 V DC. From here, there is one live wire and one return wire that leads to the next stage, i.e. the inverter. The layout of the electrical connections of the PV sub-arrays at WHF is shown in Figure 5.2:

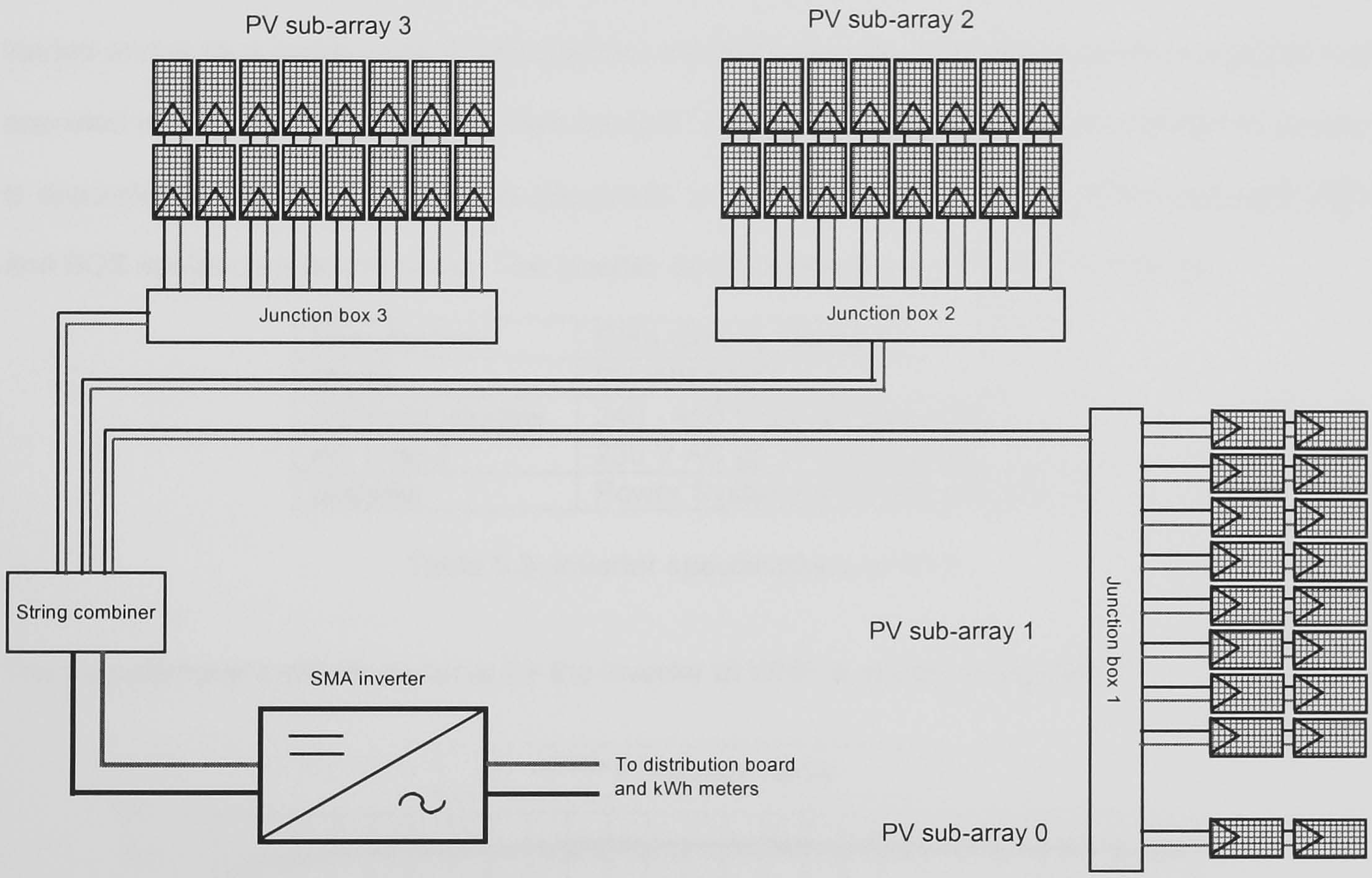


Figure 5.2: Simplified PV wiring diagram at WHF office.

5.1.2 The inverter

The inverter installed for the WHF PV array is a 5 kW line commutated thyristor inverter manufactured by SMA Regelsysteme GmbH of Germany and was supplied by Power System International Ltd. of UK. Grid integration and power measurement are being continuously monitored and controlled by this inverter. Its manufacturer's identification is PV-WR2325 and the inverter is located in the plantroom of the WHF office. The output given out by the inverter has been programmed in the original factory-installed EPROM chip, which gives an output voltage of 230 V

AC single phase, 50 Hz sine wave with nominal current at 17 A AC. The input window of the inverter has been set for an input voltage ranging from 240 to 400 V DC with a nominal current at 300 V DC and a maximum current of 450 V DC. The inverter has a built-in protection system and it would stop operating when the input DC voltage veers outside the input window, or when the output current exceeds 22 A AC. The inverter has a three phase monitoring connection with the red phase as output i.e. it monitors all three phases for a failure and if either phase goes down, the inverter is cut off automatically. Also, the wiring at the WHF is such that the red phase is the most heavily loaded and is thus being used to grid-connect the BiPV system. The WHF system is supplied and operated at a 240 V AC connection from the grid. A copy of the certified test results for the inverter is appended at the end of this thesis (Appendix A.1). The expected lifetime of the complete BiPV and BOS system are twenty years. The inverter details summary are shown in Table 5.3:

Manufacturer	SMA GmbH, Germany
Model	PV-WR 5000
DC input window	240 - 400 V DC @ 300 A DC
AC output	230 V AC @ 17 A per phase
Supplier	Power Systems International Ltd.

Table 5.3: Inverter specifications at WHF.

The manufacturer's efficiency curve for the inverter at WHF is shown in Figure 5.3:

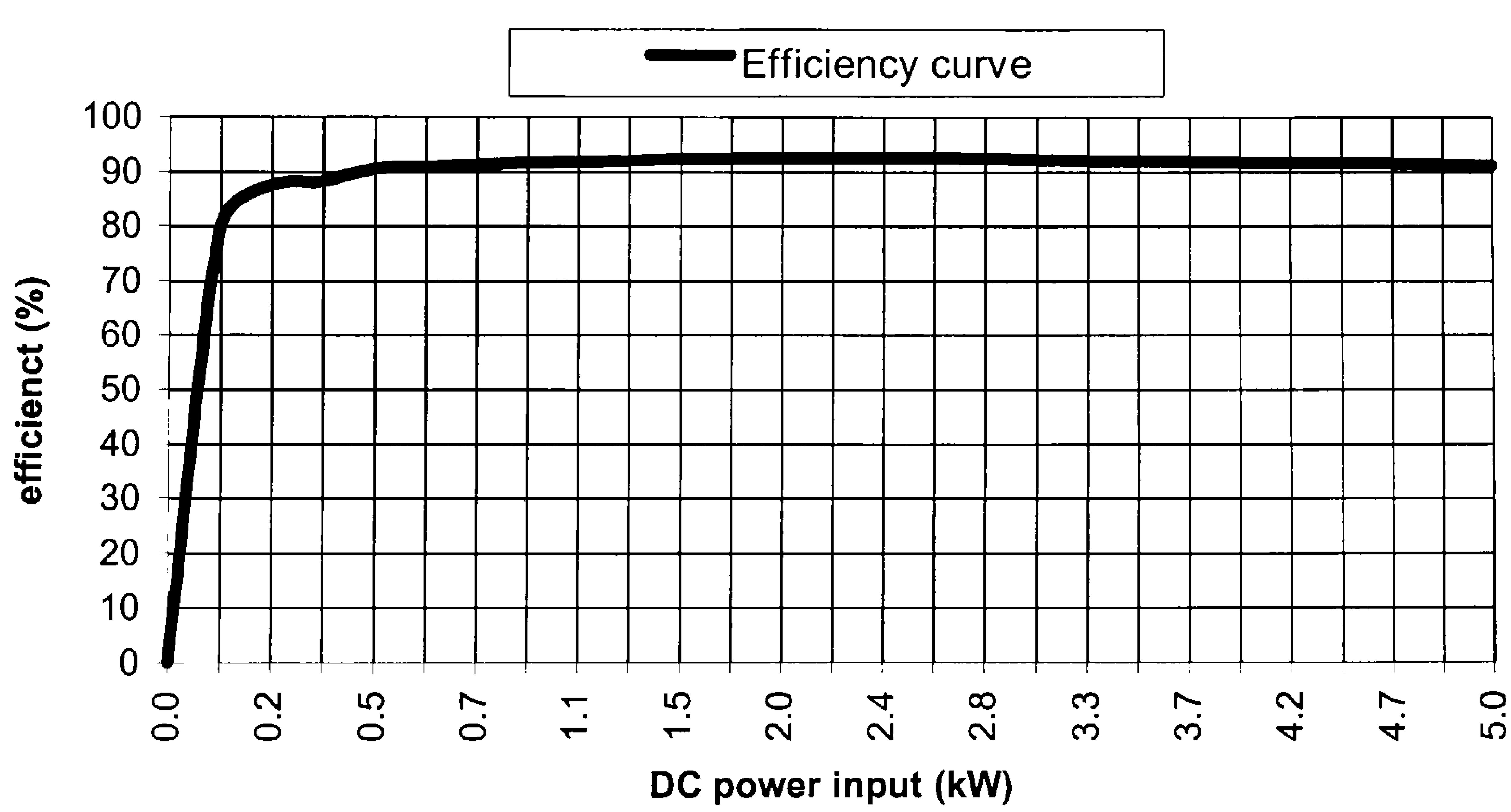


Figure 5.3: Manufacturer efficiency chart for the PV-WR5000 inverter at WHF.

5.2 Monitoring system set-up

5.2.1 Instrumentation system

The complete monitoring system installed in the research study comprised of two separate sub-systems. Sub-System 1 (SS1) involved the use of the built-in RS232 communications in the SMA inverter to which an RS cable was connected to the computer. Sub-System 2 (SS2) involved the use of a commercial stand-alone datalogger which was also connected to the computer via an optically isolated RS cable.

Only the two solarimeters and the wind anemometer were purchased together with the data logger. All other instrumentation were built and wired up separately and were then connected to their respective sensors. These had been used only with SS2.

5.2.1.1 Sub-System 1

The logging of SS1 monitored the gross power produced by the PV modules. As mentioned earlier, the monitoring of SS1 was made available through the built-up hardware of the SMA inverter and interrogated using a supplied software called the PVDATA (Power Systems International, 1987a). Retrieval of data was achieved by using the built-in RS232 port of the inverter connected to the serial communications port of a computer via a doubly shielded, earthed RS232 cable. The pre-set logging interval of the inverter has been set at fifteen minute periods and the storage depth of the memory lasts every twenty-one days on a first-input first-output basis. This was thus the most convenient determining logging interval of the whole monitoring system. A sample output of the on-screen communication printout using PVDATA is appended at the end of this thesis (Appendix A.2).

The inverter has been equipped with a 25 pin female RS port and a 9 pin female master-slave communications ports on its under-side. Of the 25 pins available, only three pins were used, namely pin 2 for reception, pin 3 for transmission and pin 7 for ground. Those pins were connected to the PC's RS232 male port on pin 3 for transmission, pin 2 for reception and pin 5 for ground, respectively. Two accompanying manuals have been supplied with the inverter, i.e. i) Installation, Operation and Maintenance of the inverter and ii) Use of the PVDATA - software for a computer-based interrogation with the inverter. The pre-set monitored parameters are shown in Table 5.4:

Parameter	Code	Range	% uncertainty
Actual PV voltage	UPV-Act	0-400 V DC	± 2
PV voltage setpoint	UPV-Set	0-400 V DC	-
Mains voltage	U-Grid	0-260 V AC	± 1
Output current	I-Grid	0-20 A AC	± 1
Output power	P-Grid	0-5 kW AC	± 2
Mains frequency	F-Grid	0-55 Hz	± 0.5
Insulation resistance PV generator	R-ISO	0-800 kOhm	± 5
Dissipator temperature	T-KK	0-90 °C	± 3 C

Table 5.4: List of monitored parameters of inverter at WHF (Power System International, 1987b).

5.2.1.2 Sub-System 2

The logging of SS2 monitored the environmental parameters and certain details of the modules. Data logging was done using a commercial stand-alone CR10 Campbell Scientific Ltd. data logger. The logger was a 12 single ended or 6 differential or with any of their combinations with the accuracy of voltage measurements at 0.2 % of full scale range. A fast single-ended voltage input sample rate was 2.6 ms. The logger processor was a Hitachi 6303 and has 32 K ROM and 64 K RAM memory with storage capacity of 29908 data values in final storage. The logger was powered by a 12 V lead-acid battery with typical current drain of 35 mA. Coding of the datalogger was done via a dedicated software called PC208E (Campbell Scientific Ltd., 1995). Coding was set such that instantaneous data was logged into the system memory at intervals of fifteen minutes into the logger, which in turn was downloaded manually every fortnight during the operations and maintenance checks. By doing so, it took about fourteen days before the memory was completely filled up and data had to be downloaded into the computer. Selected specifications of the datalogger are shown in Table 5.5:

Manufacturer	Campbell Scientific (UK)	% uncertainty
Model	CR 10	-
Channels	12 single ended	-
Sampling rate	2.6 ms	-
Power consumption	35 mA	-
Power requirement	12 V DC	-
Memory capacity	64 K	-
Analogue differential output	2.0 V	0.035
Analogue differential input	2.5 V	0.045

Table 5.5: Specifications of datalogger at WHF (Campbell Scientific Ltd., 1994).

5.2.2 Monitoring system layout

Layout for the sensors, their wiring and the control cabinet were identified and permission from the owner was sought. It was then decided that the control panel was to be placed in the plant room and the sensors and wires placed at accessible points at the site without disruption to the building. The monitoring plan at the office is shown in Figure 5.4:

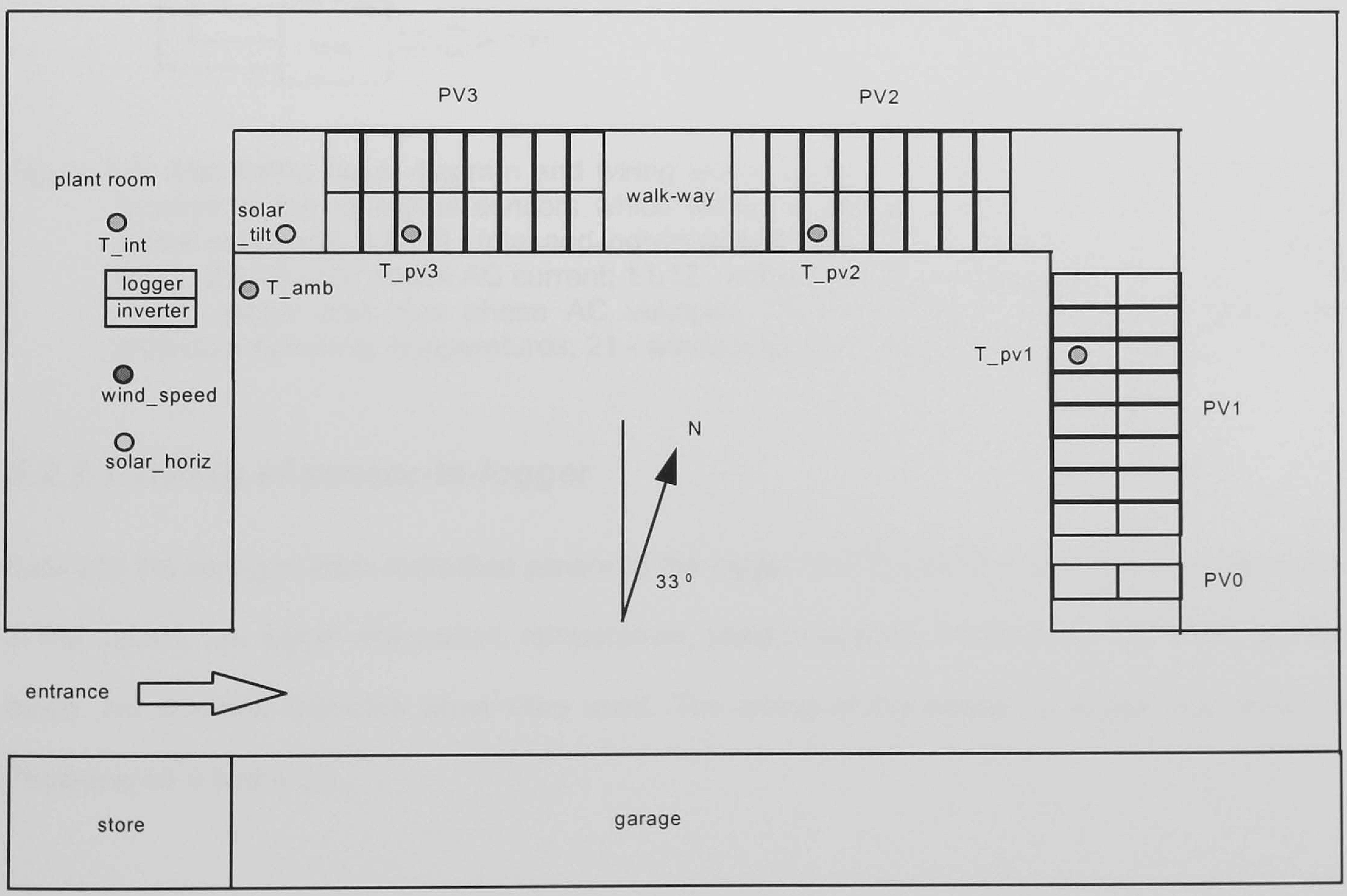


Figure 5.4: Monitoring layout plan of WHF office complex (not to scale). The sensors are: solar_horiz; solar_tilt; wind_speed; temperatures - T_amb, T_pv1, T_pv2, T_pv3.

The complete monitoring block diagram and wiring layout are shown in Figure 5.5:

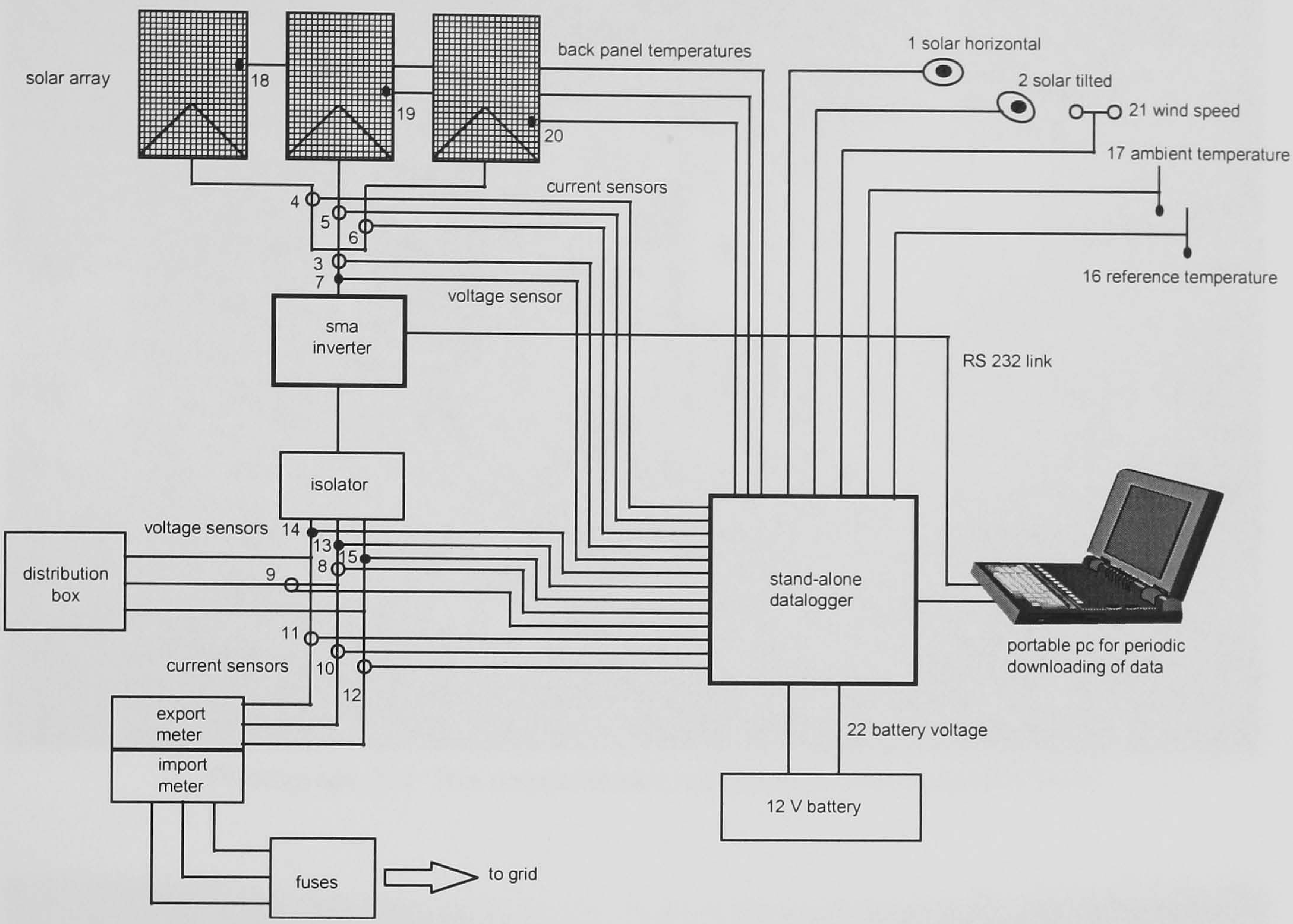
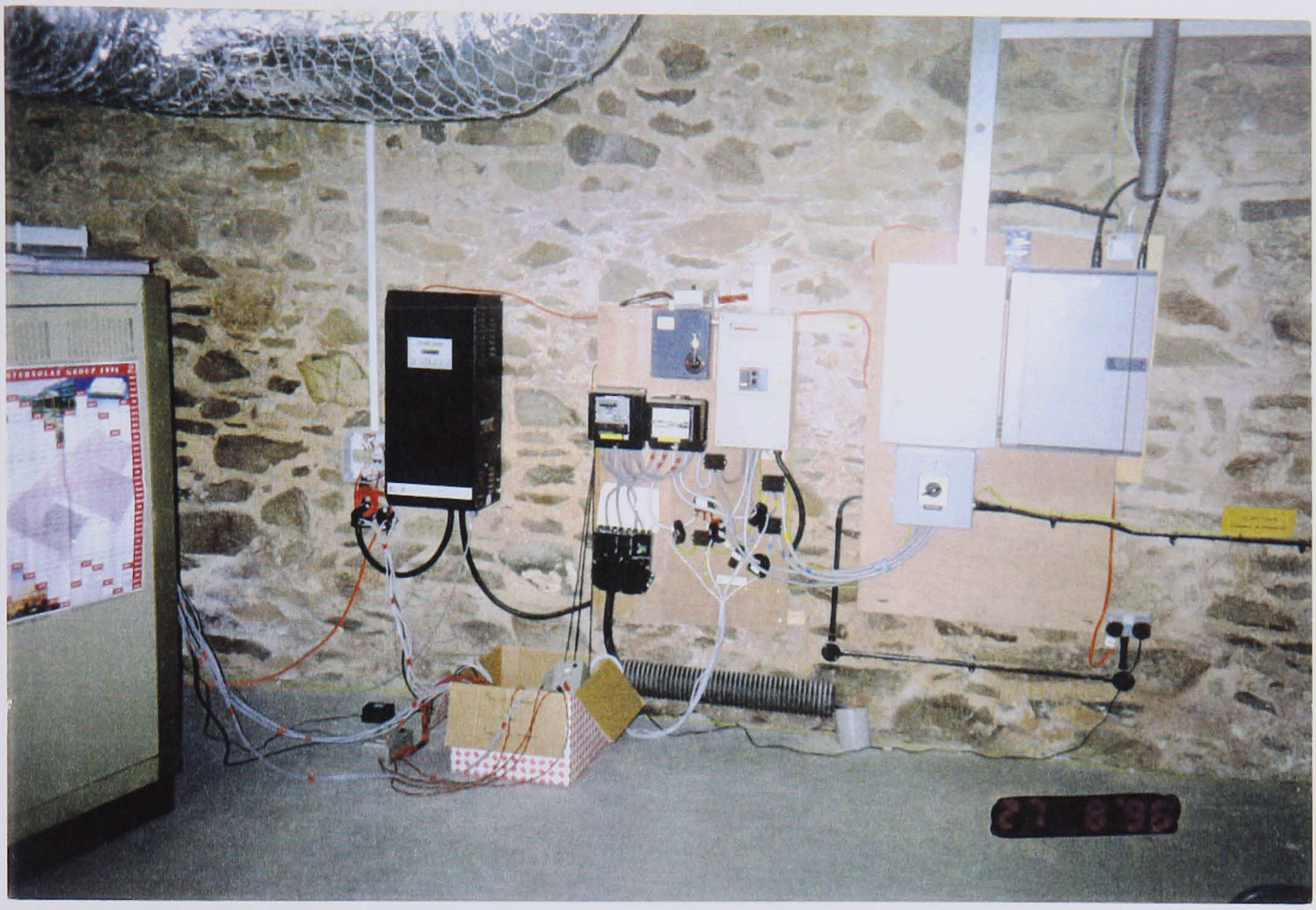


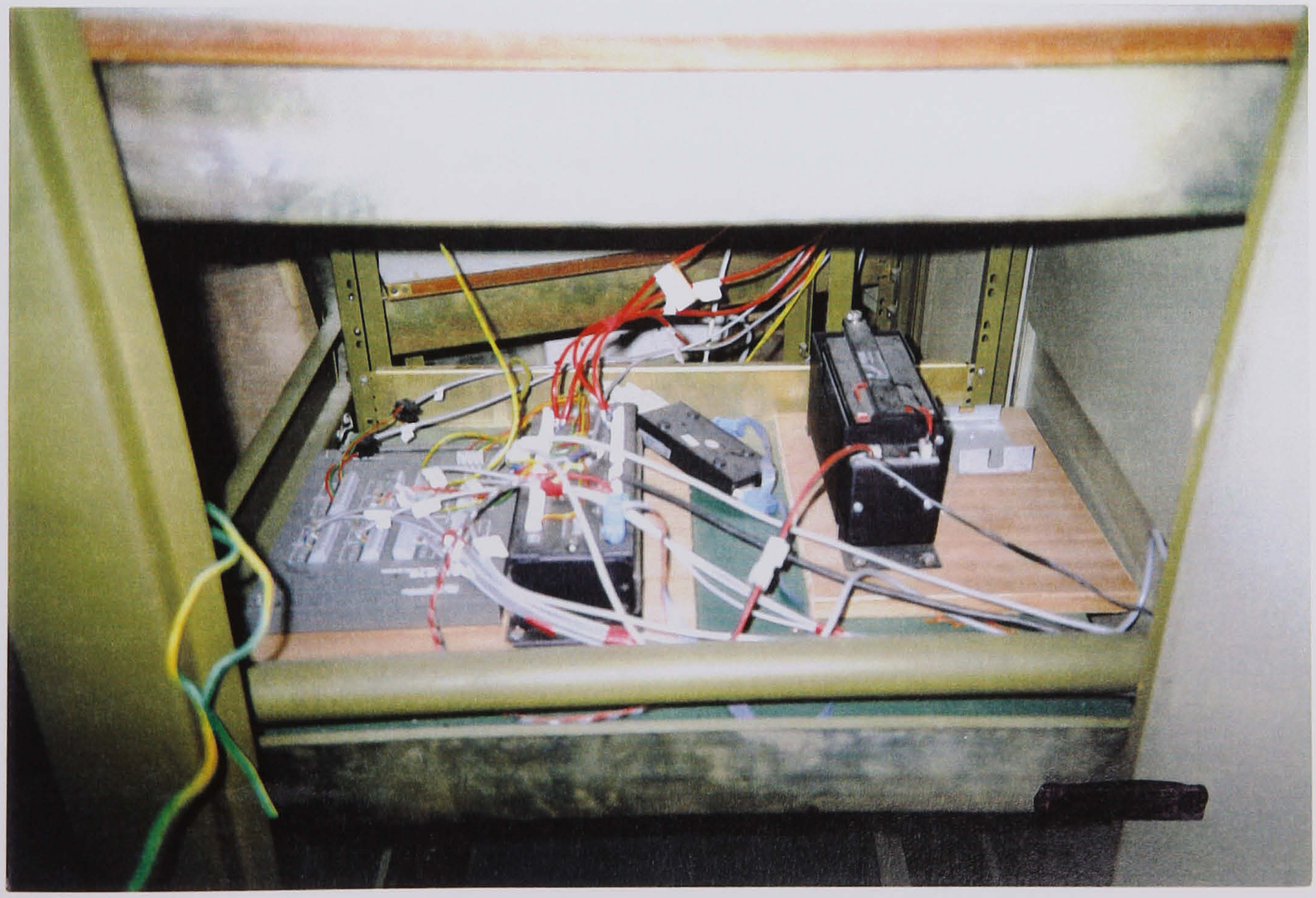
Figure 5.5: Monitoring block diagram and wiring layout at WHF. The numbered points show the location of the individual sensors which were: 1 - global horizontal irradiance; 2 - tilted global irradiance; 3,4,5,6 - total and individual sub-array DC currents; 7 - total DC voltage of array; 8,9,10 - red phase AC current; 11,12 - yellow and blues phase AC currents; 13,14,15 - red, yellow and blue phase AC voltages; 16,17,18,19,20 - reference, ambient and individual sub-array temperatures; 21 - windspeed; 22 - logger battery DC voltage.

5.2.2.1 Wiring of sensor-to-logger

Basically the wiring of each individual sensor to the logger had to take into consideration the length of the cables, i.e. signal attenuation, temperature, electromagnetic interference and humidity. For these, the shielded four-core wires were used. The wiring of the sensor to logger are shown in Photographs 5.3 and 5.4.



Photograph 5.3: The computerised monitoring system at BiPV-WHF.



Photograph 5.4: The wiring and point connections at the multiplexer and datalogger.

5.3 Sensors and transducers

5.3.1 Sensors for current and voltage monitoring

The sensors used for monitoring the currents and voltages were the Hall Effect Current Transducer (HECT) and the Hall Effect Voltage Transducers (HEVT). The DC HECT used had a measuring range of 0 to 200 A with 0 to 5 V output at an uncertainty of ± 0.6 %. The AC HECT used had a measuring range of 0 to 200 A with 0 to 5 V output at an uncertainty of ± 1 %. The DC and AC HEVT used had a measuring range of 10 to 500 V with 10 mA output at an uncertainty of ± 0.6 %. These sensors were assembled separately in the lab. Tests were made by measuring the output voltages from the output leads when a known current was passed through each coil. Different combinations of currents, voltages and loop numbers were tried. For the current sensors, the offset values for each individual transducer were obtained by passing exactly 1 A DC through the coils using a constant power supply. For the voltage sensors, standard laboratory variable voltage transformers were used for calibrations purposes. The procedure for current sensors was repeated at the site to ascertain consistent values. As the measured values obtained from the transducers were in terms of milli-Volts, all the data obtained were converted to suitable units using software programmed within the logger. Since the three PV sub-arrays were connected in parallel, the voltages of each were the same whilst the current entering the inverter was the sum of the current of each sub-array. The voltage was a logarithmic function of the current, which meant that it was also a logarithmic function of irradiance. This meant that the voltage would vary less than the current. In addition, the current generated was assumed to be directly proportional to the irradiance. Thus, in this case the current generated by the PV generator was the element of greatest interest. From the calibration of the sensors done, the recorded values of current logged by the datalogger were quite close to the real current setting values. The percentage difference between the measured current by the datalogger against the real current setting was very small with a peak at the 10 A DC mark at ± 2 %. From the observed measurements, the peak current seldom exceeded more than 9.0 A DC at any one time during the duration of the recorded data. Details of the wiring diagrams for the HECT, HEVT and calibration current graph are appended at the end of this thesis

(Appendix A.3). These transducers were then installed at the BiPV-WHF installation. For the monitoring of the DC array currents, the array cables after the string combiner were coiled-up to increase the current magnitude to better match the sensitivity of the transducers. The AC HECT were merely clamped on the existing cables. The AC HEVT were installed using a specially-built switch box to allow safe monitoring of the voltages.

5.3.2 Sensors for the ambient monitoring

5.3.2.1 Irradiance

The global horizontal solar irradiance was measured using a non-integrating SP 1110 SKYE solarimeter. It had an output measurement scale of 1 mV per 100 Wm^{-2} and an uncertainty of ± 5 %. It was placed on a suitable base, designed and constructed using 1 mm thick steel plates. The base was made in such a way that it could be inclined from 0 degrees to 180 degrees from the horizontal, with a bull-eye spirit level glued to its base to ascertain its horizontal position. The base was held to the building using a metal bracket. The bracket was then screwed onto an extended steel arm protruding from the roof making sure not to cast any shadows on the panels nor shadows of the roof casting on the sensor itself. The measurement for the tilted solar irradiance was done using a similar non-integrating solarimeter. It was simply glued onto a flat steel plate as a base on the tilted roof. It was placed near the panels but not near enough to cast shadows on the panels. However, due to architectural and economical constraints, it had a considerable amount of the time being shaded by the roofs of the East and West flanks of the building as well as the arch of the main entrance.

5.3.2.2 Temperature

The temperatures of the PV panels were measured using the RS K-type thermocouples with a measuring range of -40 to 1200 ^{o}C and an uncertainty of ± 2.5 ^{o}C. The thermocouples were adhered onto the back panel of the modules using a glued pad. Unfortunately, the tip of the thermocouples could only be placed on the back surface of the modules nearest the edge of the bottom-most panels due to architectural constraint. Their positions are shown in Figure 5.4 in an earlier section. An RS compensating cable (type VX) as thermocouple extension wire was used to connect the thermocouples to the datalogger.

5.3.2.3 Windspeed

The windspeed was measured using an A 100R vector wind anemometer with a measuring scale of 0.8 revolutions per meter and an uncertainty of ± 1 %. It had an elevated base which was constructed so that the cup was placed higher that the ridge of the roof. It shared the same bracket as the horizontal solarimeter and the instrument was earthed.

5.3.2.4 Control panel

The data logger, multiplexer, computer and printer were all housed in a salvaged metal cabinet serving as the control panel. The cabinet with its contents were placed in a corner in the plant room. The cabinet frame, anemometer and the data logger were earthed directly to an existing earth line available. The computer was earthed through the three pin plug and connected to the socket in the plant room.

With the settings described in the preceding parts, the logging of data was commenced. These final settings of the sensors were locked into the logging system after numerous initial settings had been made earlier. Actual datalogging of the BiPV-WHF installation commenced from July 1996 though to March 1997. On-site visits were done every fortnightly to check on the system as well as for the manual downloading of data.

Results of the monitoring are presented in the following Chapter.

Chapter 6. BiPV-WHF: Results, Analysis, Conclusions and Recommendations

6.1 Results of overall system performance from monitored data

A summary of the overall system performance, using the monitored data is shown in Table 6.1:

Performance	Unit	1995	1996	1997	Cum.ave p.a.
Exported energy	kWh	0.00	37.40	12.90	50.3
Total energy yield	kWh	758*	1303	233**	1314
Final yield p.a.	$kWhkWp^{-1}$	579	493	358	498
Array yield p.a.	$kWhd^{-1}kWp^{-1}$	1.59	1.35	0.98	1.36
PR p.a.	%	61	52	38	53
BiPV system eff. p.a.	%	7.9	6.8	4.9	6.8
Module cost	US$ per module	-	-	-	340
Total installed cost	US$	-	-	-	51402
Installed cost per Wp	US$ per Wp	-	-	-	19.47
PV cost per Wp	US$ per Wp	-	-	-	6.18
BiPV cost per kWh p.a.	US$ per kWh	1.07	1.25	1.73	1.24

Table 6.1: Summary of measured overall BiPV-WHF system performance. * is data weighted for 6 months; ** is data weighted for 3 months.

The daily energy yield and avoided costs for BiPV-WHF is shown in Table 6.2:

Month	Glob_Horiz (Wm^{-2})	Yield (kWh)	Avoided cost (US$)
January	180	16.9	2.15
February	232	53.7	6.85
March	420	102.5	13.07
April	*	154.0	19.64
May	*	176.8	22.54
June	*	224.6	28.64
July	439	191.7	24.45
August	395	193.6	24.69
September	270	122.6	15.63
October	303	111.9	14.26
November	232	54.1	6.90
December	121	22.2	2.83
Total p.a.	-	1424.6	181.64

Table 6.2: Average overall PV energy yield from BiPV-WHF system. Glob_Horiz - global horizontal irradiance; * - unmeasured values.

6.1.1 Total PV energy

Table 6.1 shows the overall system performance for the BiPV-WHF installation. It can be seen that the total PV energy generated by the BiPV-UK at WHF system from July till December 1995 was 758 kWh, from January till December 1996 was 1302 kWh and from January till March 1997 was 233 kWh. This gives a total generation since commissioning in June 1995 at 2294 kWh with an export of 50.3 kWh up to April 1997. Table 6.2 shows the average monthly overall PV energy generation with a cumulative total of 1,425 kWh p.a. as well as the monthly avoided cumulative costs at US$ 182 p.a. for the BiPV-WHF installation.

6.1.2 Final yield

The final yield p.a. for the years 1995, 1996 and 1997 were 579 $kWhkWp^{-1}$, 493 $kWhkWp^{-1}$ and 358 $kWhkWp^{-1}$ respectively, which gives an average value of 498 $kWhkWp^{-1}$ p.a. The value for 1997 was the lowest due to the fact that the data was taken in the Winter months only. The published UK values from the literature cited an average value between 740 to 750 $kWhkWp^{-1}$ (Dichler, 1997; Pearsall *et.al.*, 1997; Simmons, 1995; Vale and Vale, 1994). This cited value from the literature can be considered as "high" compared to the practical German experience of 700 $kWhkWp^{-1}$, considering the UK's higher latitude and having a lower solar irradiation level. Thus, the WHF final yield is about 33 % lower than the published UK average. However, results from a practical BiPV-UK at Northumbria University (NPAC) monitoring revealed that the measured final yield p.a. was only 490 $kWhkWp^{-1}$. This is closer to the BiPV-UK at WHF site and both values are thought to be realistic figures for the types of installations such as both systems.

6.1.3 Array yield

The array yield for p.a. for 1995, 1996 and 1997 were 1.59 $kWhd^{-1}kWp^{-1}$, 1.35 $kWhd^{-1}kWp^{-1}$ and 0.98 $kWhd^{-1}kWp^{-1}$ respectively. This gives and an average value of about 1.36 $kWhd^{-1}kWp^{-1}$ p.a. Published results from other sites ranged from 1.32 to 3.75 $kWhd^{-1}kWp^{-1}$ (Dichler, 1997; Pearsall *et.al.*, 1997; HAC, 1996; FhG-ISE, 1995) which gives an average of 2.54 $kWhd^{-1}kWp^{-1}$. This means that the WHF sites is about 46 % lower than the published average and about 28 % lower than the UK average of 1.9 $kWhd^{-1}kWp^{-1}$. Again the value obtained for NPAC was 1.32 $kWhd^{-1}kWp^{-1}$ making it very close to the WHF value. Thus, the WHF system is still within the UK average but resides at the lower end of the spectrum.

6.1.4 Performance Ratio

The Performance Ratio (PR) p.a. for 1995, 1996 and 1997 were about 61 %, 52 % and 38 % respectively. This gives an average PR value of about 53 % p.a. Published literature cited that for non-shaded PV panels, a typical PR ranges from 75 to 85 % (PViB Pack, 1995) and a PR below 60 % has room for improvements (FhG-ISE, 1995). Thus the WHF system is lower than the minimum value of 60 % by about 12 %. Details of this lower value are discussed later in this chapter.

6.1.5 System efficiency

The system efficiencies for 1995, 1996 and 1997 were 7.9 %, 6.8 % and 4.9 % respectively. This gives an average value of about 6.8 % p.a. Again, the value for 1997 was lowest since the data was taken in the Winter months only. From published information for UK sites, the efficiencies for NPAC was 8.1 % and for the Oxford House was 8.4 % (Dichler, 1997; Pearsall *et.al.*, 1997) which gives an average of 8.25 %. This means that the WHF system is about 18 % lower than the published UK systems.

6.1.6 Exported energy

The energy exported by the system for 1995, 1996 and 1997 were 0.0 kWh, 37.4 kWh and 12.9 kWh respectively which gives a cumulative total of 50.3 kWh. The buy-back cost agreement with the Regional Electricity Company (REC) and the WHF installation was US$ 0.0425 per kWh and the imported cost of electricity by the WHF was US$ 0.128 per kWh.

Sample graphical outputs for the BiPV-WHF installation are shown in Figures 6.1 and 6.2:

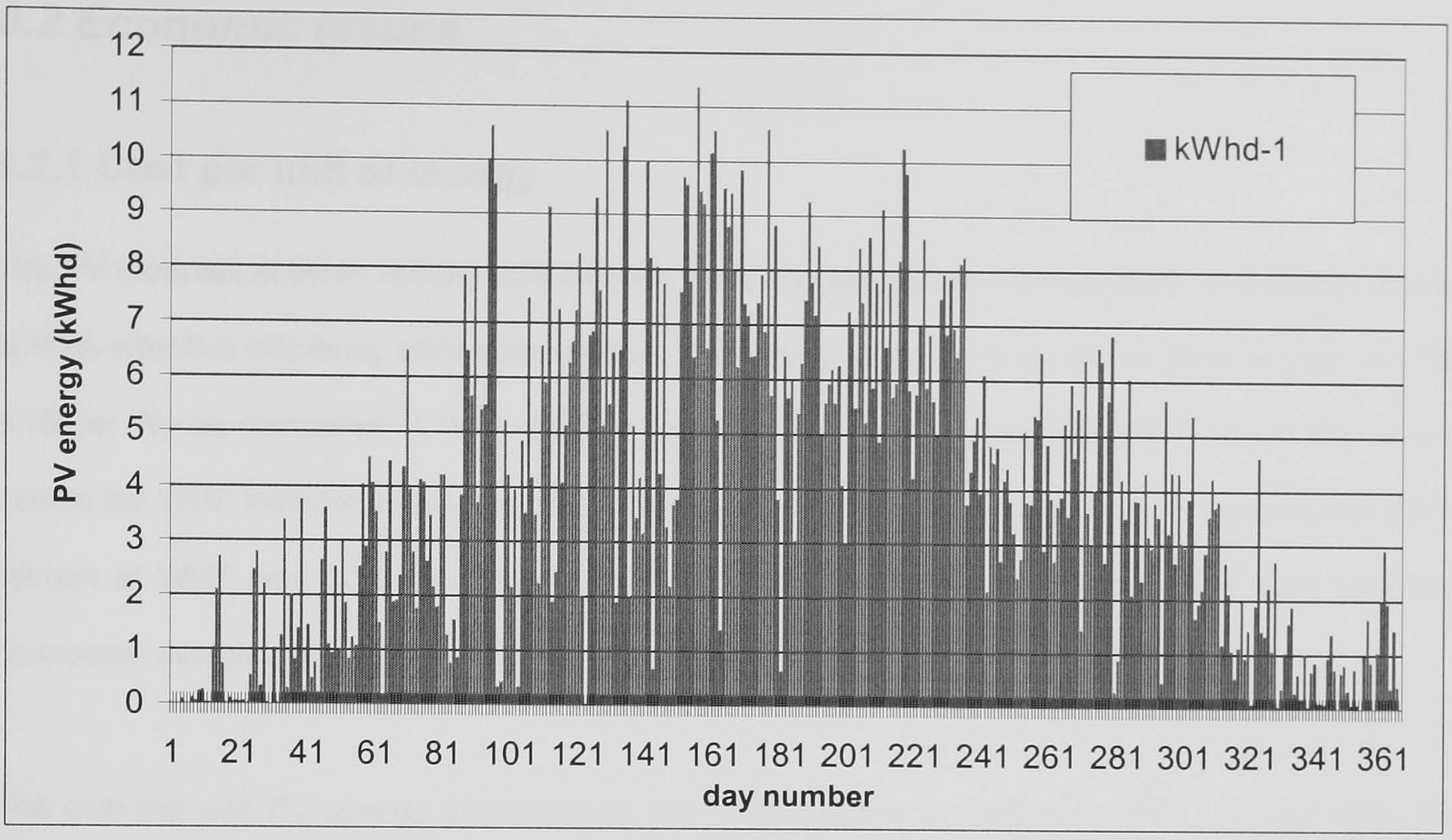


Figure 6.1: Daily PV energy generation from WHF installation.

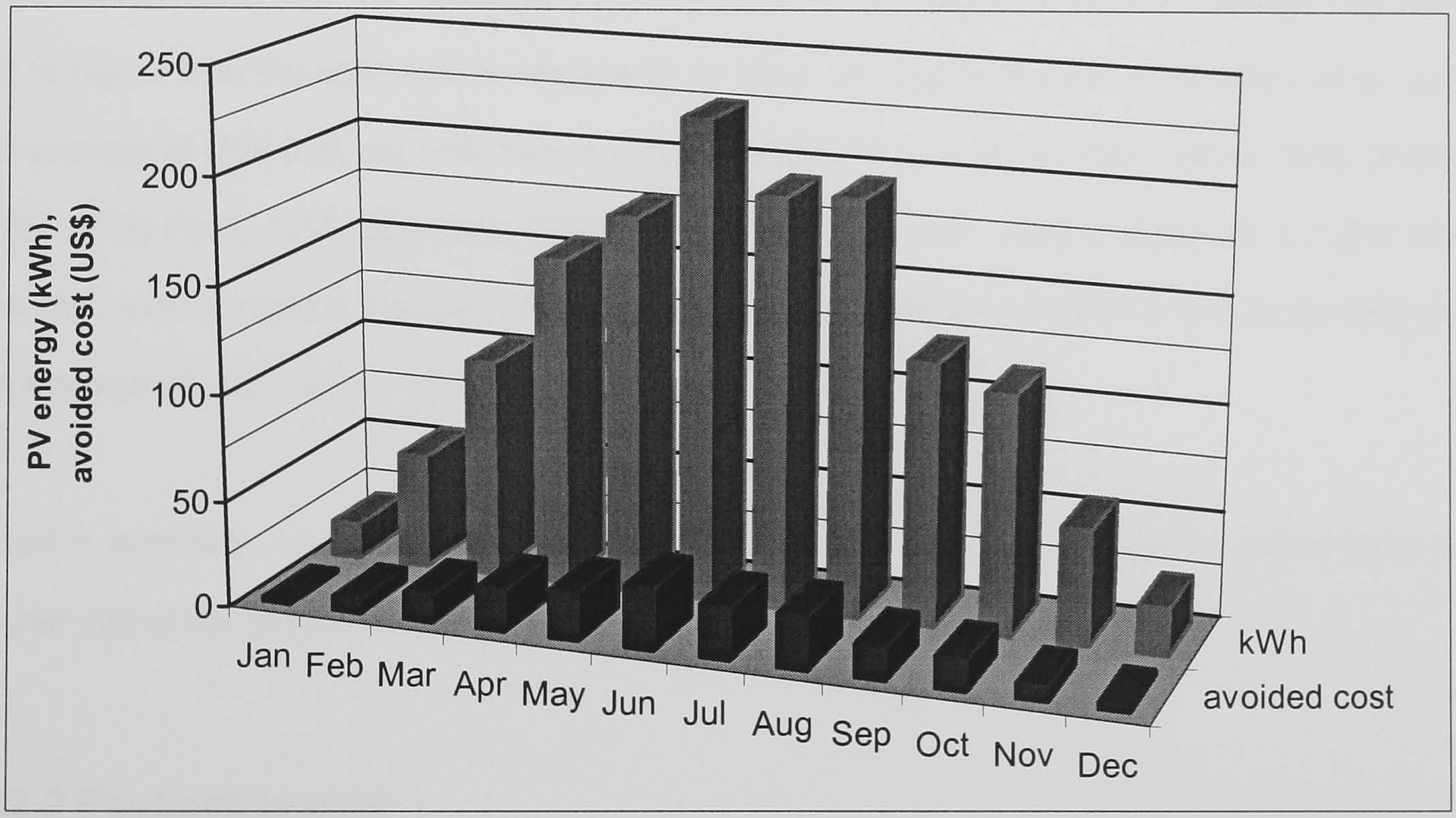


Figure 6.2: Monthly PV energy generation and avoided cost from WHF installation.

6.2 *Economic issues*

6.2.1 Cost per unit of energy

The PV modules at WHF costed US$ 340 each and the estimated optimum lifetime is twenty years, at 90% effective efficiency after deterioration. Thus the cost of modules at the WHF system is US$ 6.18 per Wp as compared to the published literature citing an average of US$ 7.74 per Wp, which makes the WHF installation at about 20 % lower than average value. The cost of the complete BiPV system at WHF was US$ 19.47 per Wp which is about 33 % higher than the present UK grid-connected systems average of US$ 14.63 per Wp.

The cost per unit PV energy generated by the WHF system in 1995 was US$ 1.07 per kWh, for 1996 was US$ 1.26 per kWh and for 1997 was US$ 1.73 per kWh. This gives an average value of US$ 1.24 per kWh over the twenty year lifetime period. This makes the WHF PV energy cost about 32 % higher than the estimated average cost for other UK grid-connected installations which gave an average of US$ 0.94 per kWh from a range of US$ 0.33 to 1.16 per kWh (David, 1996; Dichler, 1997; PViB Pack, 1995; Simmons, 1995; Roaf, 1994). This WHF value is about 88 % higher than the cited average cost in the open literature with values ranging from US$ 0.17 to 1.70 per kWh with an average of US$ 0.65 per kWh.

Thus in summary, the BiPV-WHF installation and energy generation cost was found to be at the higher end of the spectrum.

6.2.2 Payback period

The payback period for the BiPV-UK at WHF system was calculated to be 97 years. This is almost five times longer than the lifetime of the PV modules themselves, using the present costing structure. Other variations of this scenario are shown in Table 6.3:

Energy\PV	100%	90%	80%	70%	60%	50%	40%	30%	20%
100%	97	88	78	68	58	49	39	29	19
150%	65	58	52	45	39	32	26	19	13
200%	49	44	39	34	29	24	19	15	10
250%	39	35	31	27	23	19	16	12	8
300%	32	29	26	23	19	16	13	10	6
350%	28	25	22	19	17	14	11	8	6
400%	24	22	19	17	15	12	10	7	5
450%	22	19	17	15	13	11	9	6	4
500%	19	18	16	14	12	10	8	6	4

Table 6.3: Variations of the payback period for break-even at WHF installation.

From the values shown in Table 6.3, it can be seen that for the WHF system, the payback periods reach a break-even point of about twenty years if:

- The PV system costs drop to 20 % of present value.
- Its energy cost rises to 500 % of present value.
- Any combination of PV system price drop and energy cost hike.

6.3 Analysis of system performance

The complete overall system performance of the BiPV-WHF installation and cost of energy are juxtaposed with results from other installations as summarised in Table 6.4:

System		PV kWp	Solar $kWhm^{-2}d^{-1}$	Array $kWhd^{-1}kWp^{-1}$	Yield p.a. $kWhkWp^{-1}$	PR %	Installed US$ per Wp	Energy US$ per kWh
1	AMREL, LU	2.16	-	2.0	741	-	16.53	1.12
2	CAT	13.5	-	1.9	711	-	16.12	1.13
3	Homerton G.	1.62	-	2.0	741	-	-	-
4	NPAC, NU	39.5	-	1.4	494	61	15.24	1.03
5	Oxford H.	4.08	-	2.3	823	63	9.17	0.56
6	So'ton U	3.4	-	2.1	765	-	-	-
7	Vale's	2.16	-	2.2	816	-	12.75	0.78
8	WHF	2.64	-	1.4	498	53	19.47	1.24
9	Australian	-	4 - 6	> 4	1693	-	9.41	0.23
10	German	-	2.54	1.9	700	65	16.81	1.20
11	Switzerland	-	3.1	2.5	950	80	10.43	0.94

Table 6.4: Summary of overall BiPV-UK installations. 1 - Simmons 1995; 2 - CADDET No. 71, 1998; 3 - Wade, 1996; 4 - Pearsall *et.al.*, 1997; 5 - Dichler, 1997; 6 - Arnold, 1996; 7 - Wade, 1996; 8 - Shaari, 1998; 9 - CADDET-Australia, 1997; 10 - FhG-ISE, 1995; 11 - Keller and Affolter, 1995.

The values in Table 6.4 show the published average BiPV system performances and costs involved. Clearly, the Australian application gives the highest yield p.a. at 1693 $kWhkWp^{-1}$, followed by the Swiss' at 950 $kWhkWp^{-1}$, the German's at 700 $kWhkWp^{-1}$ and the UK's at 698 $kWhkWp^{-1}$. In summary, the results above show that the BiPV-UK systems generally is in the lower end of the performance range. The UK average theoretical final yield p.a. at 698 $kWhkWp^{-1}$ is very close to the German practical value at about 700 $kWhkWp^{-1}$. This is very interesting since several of the UK systems published a final yield of up to 823 $kWhkWp^{-1}$. (Dichler, 1997; Pearsall *et.al.*, 1997; Wade, 1996; Simmons, 1995; Roaf, 1994). This value can be considered as high considering the solar energy availability in the UK at 2.48 $kWhm^{-2}d^{-1}$ (CIBSE 1985) as compared to Germany's 2.54 $kWhm^{-2}d^{-1}$ (FhG-ISE, 1996 and 1995). The average final yield in the Australian BiPV system with about 4 to 6 $kWhm^{-2}d^{-1}$ solar irradiation is about four times higher than either the UK or the German values, as has been anticipated, thus giving the highest yields. The UK average installed cost at about US$ 14.63 per Wp, gives about 15 % lower than the German cost. The UK generated energy cost has been estimated to be about US$ 0.94 per kWh. Again this makes the installed BiPV-WHF system to be the most expensive. However, interestingly, the cost of generation for the UK systems theoretical average of US$ 0.94 per kWh (Dichler, 1997; Pearsall *et.al.*, 1997; Wade, 1996; Simmons, 1995; Roaf, 1994) is lower than the German practical value of US$ 1.20 per kWh. Upon closer observation, the BiPV-WHF practical monitoring reveals that its cost of generation at US$ 1.24 is slightly higher, but very comparable to the German value as would be anticipated.

Thus, in summary, the BiPV-WHF system performances found in this research project gave results that were comparable to the practical BiPV installations in Germany.

These overall system performance of the BiPV-WHF installation that have been consistently giving lower than average values within the UK, are attributed to several mainly inherent design reasons and operating problems. They can be explained as follows:

6.3.1 Architectural design

- Shading of the panels - This major issue has a significant effect on the whole system performance generally. From the very basic design of the building, it is apparent that the U-shaped building with high East and West-facing roofs flanking the walkway would give rise to a non-optimum, if not seclusion, of a considerable amount of direct solar radiation that would otherwise fall on the BiPV panels. All three different PV sub-arrays have been observed to be either completely shaded or partially shaded at different times of the day. This partial and complete shading of the cells pose a drastically inherent non-optimum generation of energy from the panels, thereby lowering the running efficiency of the system. This creates an inhomogeneous distribution of solar irradiation falling onto the PV panels. This shading problem was exacerbated in the Winter months when most of the hours in the daytime was overcast as well as shaded by the buildings own roofs about half of the daytime. This finding is in tandem with other published work relating to shading of the PV arrays (Spratt *et.al.*, 1997; Quaschning and Hanitsch, 1996; Kovach, 1994; Gabler, 1993; Overstraeten and Mertens, 1986). This can be seen from the shading charts on the panels shown in Figure 6.3 and 6.4 which indicate the amount of shading falling onto the PV arrays.

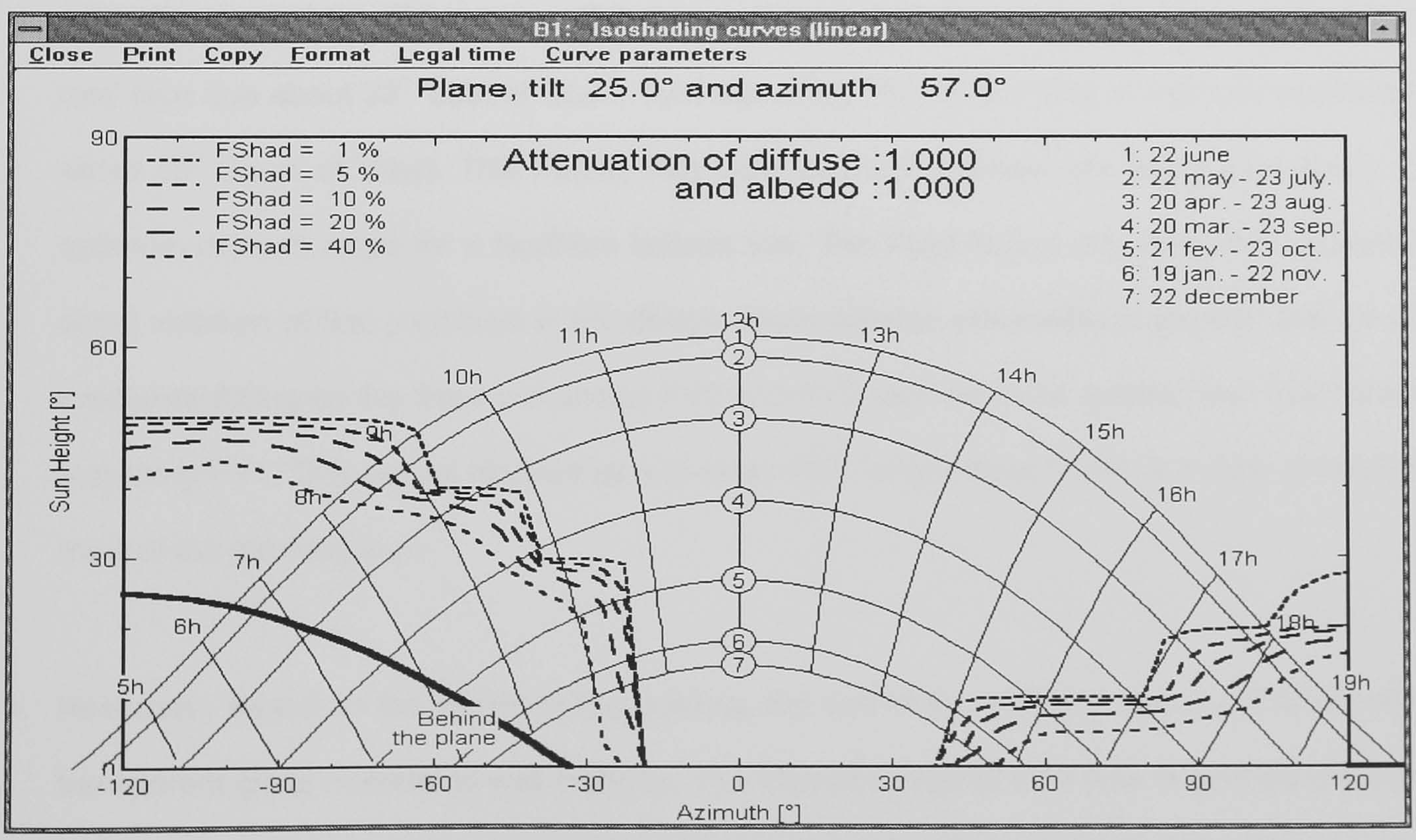


Figure 6.3: Shading chart on the sub-array PV1 at WHF. Area under the dotted lines indicate percentage of shading factor on the PV panel areas which is about 50 % of the total area.

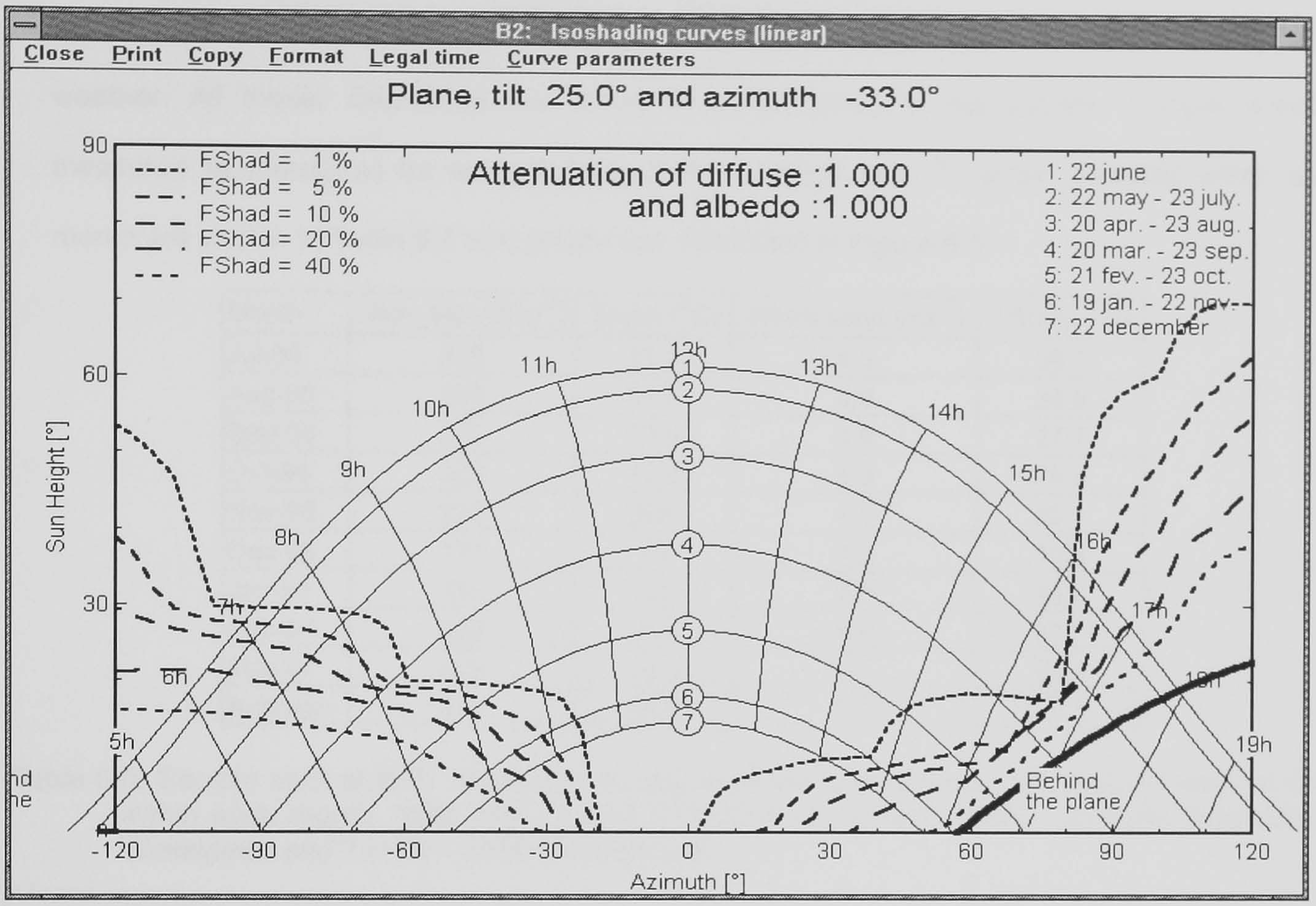


Figure 6.4: Shading chart on the sub-arrays PV2 and PV3 at WHF. Note again the extent of shading of the panels.

- Azimuth angle of the PV panels - Sub-arrays PV2 and PV3 comprising of thirty-two panels in total face due about 33° East of South. And sub-array PV1 comprising of eighteen panels faced about 33° South of West. This means that none of the PV arrays are facing due South - the optimum azimuth angle for a Northern latitude site. The West-facing sub-array PV1 is actually a direct violation of first principles in PV design. More detailed observations showed that the solar irradiance falling on the tilted sub-arrays PV2 and PV3 seemed to be greater than that falling on sub-array PV1. This seems obvious as sub-array PV1, which faces West, is mostly shaded from most of the morning sun.

- Heat trap - Based on the design of the building, the wall of the walkway has about 60:40 ratio of transparent glass material to wall material. The intended original idea was to provide pre-heated air that was to supply the boiler in the plantroom next door. This concept was made clear at the beginning of the monitoring. However, this heat trap for the air has a negative impact on the generation of power by the modules, since the panels' performance has a negative coefficient on temperature. Moreover, there seemed to be a lacking of ventilation for the panels during hotter weather. All these, decreased the would-be performance of the panels. Sample average measured temperatures for several days of the ambient and PV array, selected within each month are shown in Table 6.5 and graphically illustrated in Figure 6.5:

Month	Glob_Hor (Wm^{-2})	TAmb (^oC)	Windspeed (ms^{-1})	TArray (^oC)
Jul-96	439	21.3	4.3	38.3
Aug-96	395	17.5	3.9	36.9
Sep-96	270	13.0	3.9	27.7
Oct-96	303	12.2	6.3	25.0
Nov-96	232	5.6	4.8	20.1
Dec-96	121	1.6	4.6	10.8
Jan-97	180	7.6	3.8	16.0
Feb-97	232	7.4	8.0	18.0
Mar-97	420	13.5	6.0	28.8
Average	293	11.8	4.6	26.5

Table 6.5: Sample data at WHF showing average values of the elements for selected warmer days within each month. Glob_Hor - global horizontal irradiance, TAmb - ambient temperature, Windspeed and TArray - array temperature.

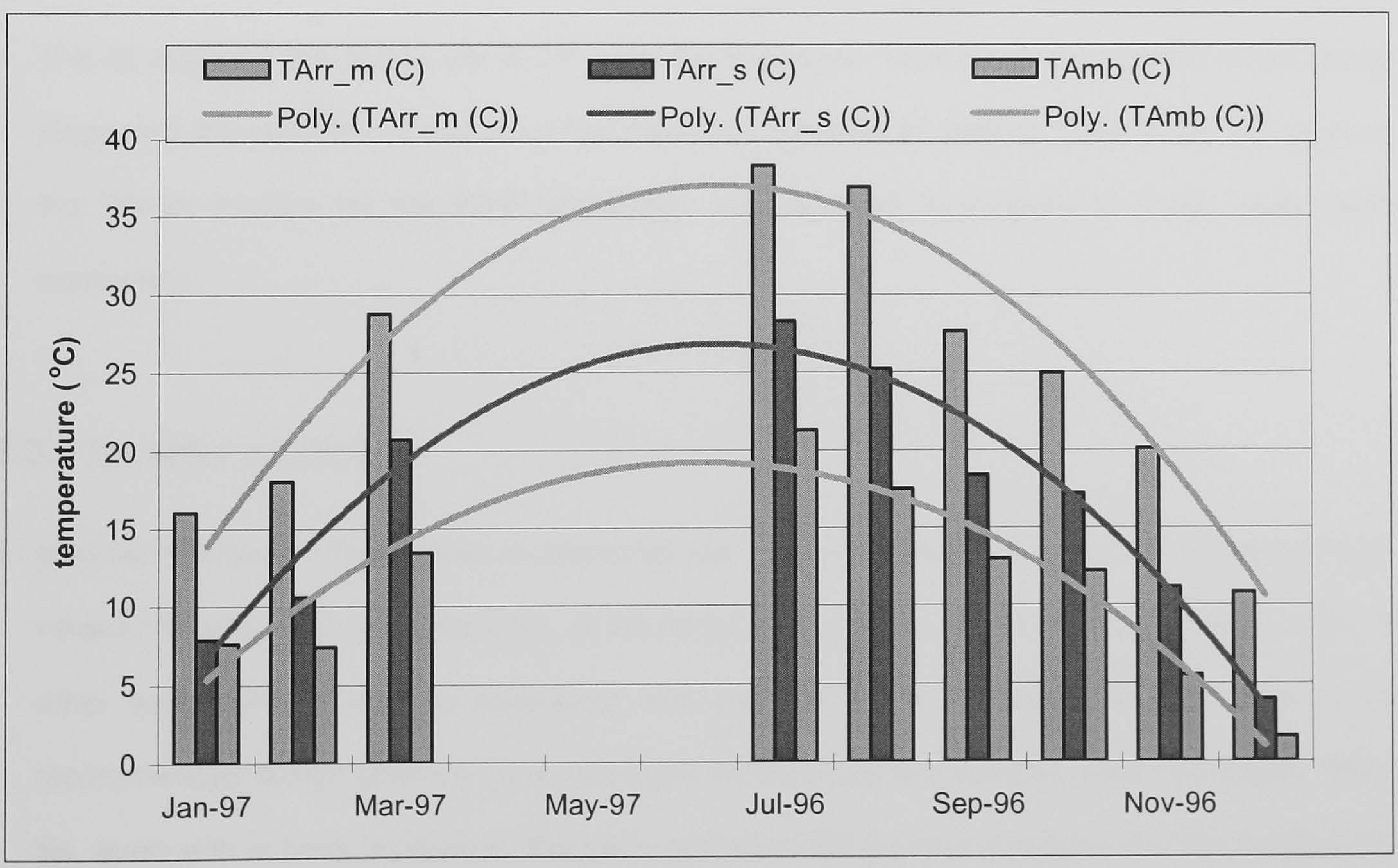


Figure 6.5: Graphical plot of the ambient and array temperature for a selected numbers of days at WHF. Poly - indicates the interpolation of data using polynomial fit.

The numbers shown in Table 6.5 are average values of the elements, for a number of selected days within a month, for the WHF installation. The chosen average values for the temperatures, were on the higher side to illustrate the possible kinds of temperatures the PV panels were experiencing. This negative effect from the higher temperatures shown in Table 6.5 lowered the system performance at the BiPV-WHF installation. The hourly measured temperatures of the arrays are discussed in more detail in the following Chapter.

6.3.2 PV array

- No-connection - The two independent PV modules that make up sub-array PV0 are not being used for grid-interaction. The modules have not been connected in any way, in anticipation of being used for monitoring purposes by the designer. However, this is a non cost-effective strategy, considering the already high cost of the modules themselves, as well as the additional cost of integrating them in the building.

- The tilt angle for the arrays are at 25° from the horizontal. This has been decided at the design stage with the rationale of capturing the maximum Summer irradiation. Thus in the UK weather, the Winter months for the WHF installation was deemed to produce a much lower yields continually.

6.3.3 Inverter system

- Inverter mismatch - The inverter is oversized with respect to the PV array i.e. an inverter of 5 kW versus PV array rating of 2.64 kWp, or the array size is about 53 % the size of the inverter. In other words, the inverter is over-sized with respect to the PV array, in opposition to the recommended design practice (Sick and Erge, 1996; Keller and Affolter, 1995; Simmons, 1995). So, even with a peak irradiance, the peak operation efficiencies designed for the inverter can never be reached, thus running at lower anticipated efficiencies. This is also worse off economically, as the extra cost of the unused capability of the inverter is left idle.

- Inverter problem - There have been innumerable trippings of the system due to over-voltage sensed by the inverter thereby switching off the system altogether. As was presented in an earlier Chapter, the original built-in EPROM chip from the manufacturer in Germany has been programmed to give an output voltage of 230 V AC into the grid. However, the grid voltage at the WHF installation has been set at 240 V AC. Thus, the inverter sensed an "over-voltage" coming in from the grid. Although this situation did not switch off the inverter completely all the time, it produced innumerable trippings since commissioning and was registered as a "fault" within the memory of the inverter. A similar situation was faced by the installation at AMREL installation in Loughborough University nearby, until the management matched the inverter export voltage by lowering the building's transformer voltage to 230 V AC. This was believed to be the same reason that has been plaguing the WHF system, which had negatively affected the system production significantly since commissioning in July 1995. Finally in November 1996, the original EPROM of the inverter was replaced with a new one which caters a wider window, and ever since, no new faults have been registered. Only the last twenty fault occurrences are registered in the inverter memory and a printout of this list is appended at the end of this thesis (Appendix A.4). The average efficiency during operation of the inverter has been well within the acceptable range given the uniqueness of the WHF installation. As an example, it recorded an average peak of about 90% during sunlight operation times for August 1996 and 84% for September 1996.

6.3.4 Others

- Dust - There have been the accumulation of dust on all of the panels during long dry spells and bird droppings on a few of the cells. This was evident to the touch with a clean finger and by visual inspection. However, downpours seemed to have a cleaning effect of dust accumulation on the panels as observed to the touch. Snow accumulation on the panels also seemed to have a cleaning effect on the panels as it melted down.

6.4 Conclusions

Values from both the monitored data and the simulated results at the BiPV-UK at WHF installation have been analysed and discussed. With regards to the analysis and interpretation of results from the preceding section, it can be concluded that:

1. The overall system performance for the BiPV-WHF installation is consistently at the lower end of the spectrum as compared to other estimated averages for grid-connected PV systems. The BiPV-WHF gave an overall system performance with a final yield of 498 $kWhkWp^{-1}$ p.a., an array yield of 1.4 $kWhd^{-1}kWp^{-1}$ and a PR of 53 %.

2. The economic cost of the WHF system is on the higher end compared to the average costs of generation for other grid-connected system. The BiPV-WHF system has an installed cost of US$ 19.47 per Wp, a cost of generation at US$ 1.24 and a payback period of 97 years.

3. The monitored data showed performances that are realistic of such installations such as in the UK climate, comparable to the practical German experience.

4. There appeared to be several opportunities that could up-grade the BiPV system performance at WHF. The major opportunities are mainly seen at the architectural and wiring design stages and these are discussed in the next section.

6.5 Recommendations

Suggestions to up-grade the system generation of the BiPV-UK at WHF installation are presented and discussed according to the categories as follows:

6.5.1 Short term-lower cost measures

1. The simplest suggestion is to make use of the two already installed but grid-unconnected PV modules presently designated as sub-array PV0. This will increase the peak capacity at WHF up to 2.75 kWp from the present 2.64 kWp or by about 4 %.

2. A second suggestion is to consider permutational combinations of the series-parallel connections of the present system with the 5 kW inverter. This simply means that the present connections need to be reconfigured and rewired so that the total generated power is at a maximum after taking into consideration the shadings on some of the panels on the various permutational configurations.

6.5.2 Medium term-higher cost measures

3. The WHF system can use several smaller string inverters instead of one bigger inverter as in the present situation. This will improve the matching between the array configuration of the modules and the inverters, so as to be within the optimum architectural layout and microclimate at WHF. This can be done by using three better-matched inverters for the three PV sub-arrays. The SMA family of inverters are capable of being used in cascade, i.e. being switched on one at a time depending on generated capacity in a master-slave connection.

4. A further optimisation measure can be taken by sizing each PV sub-array to about 120 % to the size of each individual inverter. Also, the shaded panels can be connected to the last of the cascading inverter as and when the generation exceeds the first two inverters. The present 5 kW inverter can be salvaged for other applications.

5. Another suggestion is to use module inverters for each PV module. Permutations of the series-parallel connections must again be worked out taking into consideration the shadings of the modules as before.

6.5.3 Long term-highest cost measures

6. This involves the matching up of the array capacity to the installed inverter. The existing SMA 5 kW inverter can take up to about 20 to 80 % of overload (Sick and Erge, 1996, Keller and Affolter, 1995; Simmons, 1995). The overloading is expected to be in short spans of time in the normal circumstance, but with the WHF architectural layout, this is expected to be at a minimum. Assuming a PV to inverter ratio over-sizing of about 50 %, this means installing extra PV modules to reach a peak capacity to about 7.5 kWp. This requires an extra of 86 Siemens M55 modules with a total cost of about US$ 30,000 without installation. This about doubles the installation cost of the existing system. Then again a permutational combination of the modules wiring configuration needs to be done, to obtain the optimum generation. Also the architectural constraints of the area for the new panels must be considered.

6.5.4 Alternate suggestion

1. The PV arrays seem to be better placed as roofing material of the main building above the conference room. This seems to be very natural as the central roof is the highest and architecturally less seclusive to solar radiation except maybe in the very early mornings. All of the modules can form this roof and a suitable series-parallel connection can be configured and wired. Also by using suitable PV material, this PV roof can provide daylighting into the rooms below. However ventilation of the PV roof must be designed properly to ensure optimum operation. This measure is best taken at the architectural design level right from the beginning.

6.5.5 General remarks

With regards to the BiPV system and monitoring tools used at the WHF installation, general remarks are made as follows:

- With regards to the RS communication with the inverter, there appeared to be some unstability in the software communication. As a case in point, in some instances the software hung up when the graphical display mode was invoked from within the main programme. Also, the downloading of long-time data had been suffering from hiccups, whereas other on-line requests had been operating smoothly. Even with the use of special RS232 communication cables, these hiccups had been persistent. It was thought that the problem was due to the high strength of the electromagnetic noise within the working area as well as a corrected version of the software was needed.

- The Campbell Scientific CR10 datalogger proved to be a versatile and reliable stand-alone tool for datalogging and monitoring, especially for environmental and certain energy parameters.

Chapter 7. Selected BiPV Computer Models and Validation of PVSYST 2.0

7.1 Background and literature review

A survey of the various specialised BiPV computer models was made through literature search. Traditional methods of searches for physical materials (e.g. reviews and advertisements in journals, articles, pamphlets and books) in libraries as well the World Wide Web (WWW) were tried. It was found that for this particular type of a search, using the WWW proved to be a far more superior method than the traditional method. This was demonstrated when the WWW searches offered on-line demonstrations of the computer models or even the real models or softwares themselves (with limited capabilities) for a free trial period. This provided a fast and easy way to zoom in and analyse the softwares.

The computer models looked for have to be able to simulate results as close as possible to realistic performances. At the same time, they have to be able to handle numerous data of the climate, PV components and building integration (ETSU 1997; Kaiser and Reise, 1996). Other points that were considered included realistic Graphical User Interface (GUI) and exportability of simulated results into other formats as these were the latest developments and trends in solar PV simulations models or softwares (TRNSYS-14.2, 1996; Kaiser and Reise, 1996; Negro, 1994, O'Sullivan *et.al.,* 1994). These points were noted as softwares tended to increase in complexity, whilst one of the main factors involved in the project from the onset was to produce results that could be easily learnt and reproducible by as many users as possible in Malaysia. Based on the issues mentioned in the preceding paragraphs, the selection of a suitable BiPV computer model for this project was based on: a) reliability, b) flexibility, c) user-friendliness, d) portability and e) lower-cost.

Numerous contacts with personnel in institutions within the UK were sought after. These included several UK universities, UK companies and UK PV demonstration sites. Enquiries relating to experience in the use of specialised BiPV computer models were made. It was found that there existed one PV computer model developed within the UK at the University of Reading, but that it was not available commercially at the time of writing (ETSU, 1997; Bahaj 1996). Positive as well as negative responses from these sources led to making the search wider within Continental Europe and North America. Further correspondences led to the Fraunhofer Institute - Institute Solare Energiesysteme (FhG-ISE) which had done a similar search earlier (Kaiser and Reise, 1996). A similar search was later being done within the UK and had only been very recently published (ETSU, 1997).

Literature searches done included reports and reviews of PV computer models like: ASHLING from the National Microelectronics Research Centre, Cork, Ireland, SOMES from Utrecht University, The Netherlands, PVPACK from Karlsruhe University, Germany, PVS from the FhG-ISE, Germany, and demonstration versions of some of the softwares which included: INSEL from the University of Oldenburg, Germany, TRNSYS from the University of Wisconsin, USA, SOLARSIZER from the Center for Renewable Energy and Sustainable Technology (CREST), USA, PVSYST from the University of Geneva, Switzerland and WATSUN from the University of Waterloo, Canada. Other PV related softwares available in the market are shown in Table 7.1:

Year	Type	Model name	Originator	Country
1988	SIM	PVFORM	Sandia National Laboratory	USA
1989	SIM	PHOTO	Helsinki University of Technology	Finland
1992	SIM	PVnode	ZSW Baden-Wurttemberg	Germany
1992	SIM	SHADE	ZSW Baden-Wurttemberg	Germany
1993	SIM	DAST-PVPS	Universitat Munchen	Germany
1993	SIM	PVPUMP	Fachhochschule Koln	Germany
1994	SIM	FWISO 81	NES Neue Energie System	Germany
1994	DB	ISEE	Institut fur Solare Energieversorgungstechnik	Germany
1994	SYS	ITE-BOSS	ZSW Bade-Wurttemberg	Germany
1994	TAB	PVcalc	Oberosterreichische Kraftwerke AG	Austria
1994	SIM	PVDIM	GENEC	France
1994	SIM	PV-TAS	Universitat Oldenburg	Germany
1994	SIM	PV	Oberosterreichische Kraftwerke AG	Austria
1995	SIM	PV-DIMM	Jensolar GmbH	Germany
1995	TAB	PVF-CHART	University of Wisconsin	USA
1995	SIM	PVSHAD	Universitat Oldenburg	Germany
1996	SIM	PVS	FhG-ISE	Germany
1996	SYS	SOLARSIZER	CREST	USA

Table 7.1: List of some commercial PV computer models available (ETSU, 1997; Kaiser and Reise, 1996; Sick and Erge, 1996). TAB - tabular statistical procedures; SIM - time step simulations; SYS - simulation systems; DB - databases.

It is interesting to note that a majority of the listed commercially available PV computer models are from Germany, while there is none from the UK. It is believed that major companies such as Siemens and BP Solar, use their own internal software, not made available for commercial use. Of special interest relating to this research project are the dedicated BiPV computer models. A range of the commercially available computer models for BiPV applications, were searched, selected and evaluated. Basically, these BiPV software can be generally categorised into three major classes as follows (Kaiser and Reise, 1996):

- Statistical - these programs predict PV systems performances by using extensive statistical data.

- Time-step simulation - these programs predict PV systems performances by using pre-defined characteristics of sub-systems and forming the complete system by connecting the different sub-systems together.

- Simulation - these programmes predict PV systems performances from the ground-up using basic computer programming languages.

It has been reported that the time-step simulation procedures were predicted to be the successful mode of prediction in the future (Kaiser and Reise, 1996). Other publications stated that many softwares were very difficult to use for designing systems, as they required inputs that were not available and were highly variable, or required considerable knowledge in PV systems and computational expertise (ETSU, 1997; Kaiser and Reise, 1996).

7.2 Evaluation of BiPV computer models

As stated in the preceding part, the search for the BiPV computer models was based on several requirements. Upon successful searches, several of the softwares were chosen. A summary of the evaluation form for the specialised BiPV computer models is shown in Table 7.2:

			ASHLING 5.0	INSEL 4.8	PVS	PVSYST 2.0	SOMES 3.1	TRNSYS 14.2
Price	1	base package	NA	DM 500	DM 890	CHF 400	DFL 250	US$ 2000
	2	technical support		Y	Y	Y		Y
	3	validation		Y		Y	Y	Y
Analysis	1	simulation basis	time-step	systems	time-step	time-step	time-step	systems
Hardware	1	IBM compatible	Y	Y	Y	Y	Y	Y
	2	kBytes RAM		640		2 M		
	3	coprocessor	Not necess.	Highly recom.	Not necess.	Not necess.	Not necess.	Not necess.
	4	graphics card		Y				
Type of applica tions	1	direct DC	Y	Y	Y	Y	Y	Y
	2	stand-alone	Y	Y	Y	Y	Y	Y
	3	grid-connected	Y	Y	Y	Y	Y	Y
	4	facade				Y		
	5	controller	Y	Y	Y	flexible	Y	Y
	6	hybrid stand-alone		Y	Y	Y	Y	limited
	7	shading factor			Y	Y		
	8	inverter library	Y		flexible	flexible		
	9	module library	6 types	7 types	flexible	flexible	1 type	
	10	tilted	Y	Y	Y	Y	Y	Y
I/O feature	1	met data library	Y	Y	Y	Y	Y	Y
	2	met generator	Y	Y	Y	Y	Y	Y
	3	met graphic	Y	Y		Y		Y
	4	import/read data				Y	Y	
	5	energy analysis			Y	Y	Y	Y
	6	eff. graphics			Y	Y		
	7	comparisons				Y		
	8	PR calculations			Y	Y		
	9	economics				Y	Y	
User inter-action	1	operating system	Windows	DOS	Windows	Windows	DOS	Windows
	2	input with mouse	Y		Y	Y		Y
Types of output	1	on screen	Y	Y	Y	Y	Y	Y
	2	printout	Y	Y	Y	Y	Y	Y
	3	delimited output		Y	limited	Y	Y	Y
	4	graphic display		Y	Y	Y	Y	
Others	1	manual	Y	Y	Y	Y	Y	Y
	2	Available now?	Y	Y	Y	Y	Y	Y

Table 7.2 : Summary checklist of selected solar PV computer models. Y - yes; flexible - means the package has built-in library that can be expanded by the user; limited - means the package can only perform a minimum range of commands.

The establishments and institutions that developed the selected computer models are shown in Table 7.3:

PV model	Originator
ASHLING 5.0	Nat. Microelectronics Research Centre, University College, Cork, Ireland
INSEL 4.8	Dept. of Physics, University of Oldenburg, Germany
PVS	Fraunhofer Institute - ISE, Freiburg, Germany
PVSYST 2.0	Group of Applied Physics, University of Geneva, Switzerland
SOMES	Dept. of Science, Tech. and Society, Utrecht University, The Netherlands
TRNSYS 14.2	Solar Energy Lab, University of Wisconsin, USA

Table 7.3: Originating addresses of selected PV related commercial computer models.

Following are descriptive summaries of the basic features of the selected BiPV computer models:

7.2.1 ASHLING 5.0

This model was developed as an EC Joule II renewable energy project and jointly written by authors at the National Microelectronics Research Centre, University College at Cork, Ireland and Centre d'Energetique, Ecole de Mines de Paris, France. Its latest advancement was the introduction of a realistic Graphical User Interface (GUI). This simply means that the input components in the software comprise of realistic looking icons that can be clicked, dragged and dropped into the working space in the software. This eliminates difficulties users typically have when dealing with textual type input which have been dominant in many earlier developed softwares (O'Sullivan *et.al.,* 1994). However, ASHLING 5.0 seems not to follow through with its simulations in that important calculations like solar fraction and performance ratios have not been included. This programme has yet to be validated with real systems (Kaiser and Reise, 1996).

7.2.2 INSEL 4.8

This model first appeared in 1993 from an author in the physics department at the University of Oldenburg, Germany. It is based on 2-D block diagrams of pre-defined components. It appeared to be one of the more complicated softwares at the time, in the sense that it can be used to simulate non-standard PV systems besides conventional ones. Furthermore, the time step for simulations is at the discretion of the user, unlike most other softwares which have a default of hourly calculations. However, INSEL 4.8 does not have the facility to read or import met data and one's own measured data from data files. Instead, INSEL 4.8 generates them from simulations (Kaiser and Reise, 1996;

INSEL 4.8 Manual, 1993). A demonstration version of INSEL 4.8 was examined and from experience, it can be said that INSEL 4.8 is a difficult software to work with. Also, INSEL 4.8 is not a menu-driven software and the author has been making efforts in updating it to be used in a Windows environment. However, at the time when it was required, INSEL 5.0 for Windows had not been made available (Schumacher, 1997).

7.2.3 PVS

This model was developed at the Fraunhofer Institute for Solar Energy System. It is a Windows-based menu-driven software based on a time-step procedure (Schellbach, 1997). Its calculations require and produce one hourly time step simulations. A major limitation of the software is that only some of the hourly quantities of the calculated data could be exported into ASCII format for further processing. It also does not provide a detailed analysis of the operating behaviour of the PV system. Another limitation of PVS is that it has not been extensively validated with real systems at the time of search (Kaiser and Reise, 1996). However, at the preliminary level, PVS has been considered to be the "best-buy" although there are some difficulties in adding new weather data and customising the format of output results (ETSU, 1997).

7.2.4 PVSYST 2.0

This model was developed by an author at the Group for Applied Physics, University of Geneva, Switzerland. This software has been designed to be used specifically for BiPV systems (Mermoud, 1995). It is a menu-driven software with a flexible capability for expanding the library of components. The more advanced features of PVSYST included: a basic 3-D geometric construction of an active system with shading calculations, a comparison output of measured data versus simulated calculations and a vast array of built-in graphical output menus. These features have not been available in any other models present in the market at the time of the searches. Moreover, at every stage of the way, a wealth of on-line graphical outputs are made available as didactic tools and quick physical interpretations, all exportable in ASCII form. More importantly, PVSYST 2.0 is capable of modelling a realistic BiPV simulation taking into account the various effects and influences and is able to analyse the operating behaviour of a system in detail (Kaiser and Reise, 1996; Mermoud, 1995; PVSYST 2.0 Manual, 1996). A demonstration version of PVSYST 2.0 was evaluated and it was found that this software proved to be very flexible and comprehensive. PVSYST 2.0 has been considered to be "the most comprehensive tool" but "requires considerable PV and computing expertise" (ETSU, 1997).

7.2.5 SOMES

This model was developed at the University of Utrecht in the Netherlands. It is a DOS-based software that evaluates technical and economical performance of a PV system. SOMES speciality is to simulate stand-alone PV-wind-hybrid systems with economic calculations. However the types of PV modules incorporated are very limited in choice and it does not have an inverter library (Kaiser and Reise, 1996). Like most softwares, it uses a one hourly time step in its simulations.

7.2.6 TRNSYS 14.2

This model was designed primarily and developed originally as a solar thermal simulation system at the Solar Energy Laboratory, University of Wisconsin, Madison, USA (TRNSYS 14.2, 1996). Later developments included some PV components in the software, which were added by several users (Fiksel *et.al.*, 1994). A demonstration version of TRNSYS 14.2 for Windows was evaluated and revealed that TRNSYS 14.2 did not produce outputs similar to or beyond those of more specialised BiPV softwares, like PVS or PVSYST 2.0.

7.2.7 PVPACK

This model has not been listed in the evaluation Table 7.2 simply because of two major reasons: i) it is not available for public use and ii) it is UNIX-based i.e. non-portable PC-based system (Kovach, 1997). However, it is worth mentioning that "PVPACK is a simulation tool which is specifically designed to determine the energy output of building-integrated PV arrays experiencing an inhomogeneous irradiation distribution caused by shading or reflections in urban surroundings"

(Kovach, 1994). Thus PVPACK is a specialised BiPV software and comprises of a conglomorate of four models: i) TRNSYS - for weather data generation ii) RADIANCE - for processing building descriptions and calculating irradiation levels iii) RADGEN - for normalising TRNSYS output and RADIANCE output as well as calculating partial shading, and iv) PVIRR - for simulating PV array performances. This software has been validated against measured data in Fresno, USA and in Freiburg, Germany. At the time of writing, PVPACK was not available and was under-going further developmental advancements that deal with partial shading of the PV cells (Reise, 1997).

7.2.8 SOLARSIZER

This commercially available model was a Windows-based PV computer model, that was developed by the Center for Renewable Energy and Sustainable Technology (SOLARSIZER, 1997). A demonstration version was tested and it was found that SOLARSIZER was very easy to be used. However, SOLARSIZER has been intended for simulations of elementary stand-alone systems only, and lacks flexibility and is non-comprehensive. The met data library is mostly for the USA and the components library is not as extensive as others. It was thus considered unsuitable for the purposes in this research programme.

7.2.9 Computer model chosen for BiPV work

Based on these findings, it was concluded that the most suitable BiPV computer model commercially available, that seemed best meeting the needs of the work within this research programme for the specified Malaysian type of use was PVSYST 2.0 from the University of Geneva, Switzerland.

7.3 PVSYST 2.0

The computer model PVSYST 2.0 has already been validated extensively by the author (PVSYST 2.0 manual, 1996; Mermoud, 1995). The validations were done for seven different types of Swiss installations ranging from 0.4 to 100 kWp at various running stages of the software. The validations carried out were for hourly and sub-hourly time periods over one year. In summary, the validation work on the computer model as reported by the author gave the performance statistics shown in Table 7.4:

Parameter	Irradiation	Panel temperature	PV field	Global AC output
MBE	-11.3 to 9.3 %	-0.7 to 0.8 C	-13.6 to 5.6 %	-12.8 to 5.5 %
RMSE (daily)	2.9 to 9.6 %	-	2.2 to 10.8 %	2.4 to 12.7 %
RMSE (hourly)	5.1 to 11.7 %	1.5 to 3.8 C	5.2 to 17.7 %	5.5 to 19.0 %

Table 7.4: Validation statistics of PVSYST 2.0 done by author (PVSYST 2.0 manual, 1996). MBE - Mean Bias Error; RMSE - Root Mean Square Error. Negative sign indicates the model underestimated measured values.

7.3.1 Models used in PVSYST 2.0

7.3.1.1 Irradiation model

The model uses the concept of an "effective incident irradiation" of the luminous energy impinging on the panels. It uses the global and diffuse irradiances on the horizontal and calculates the effective values after taking into consideration elements from near and far shading corrections. The software includes an algorithm for shading factor calculations. If the diffuse data is not available, the model uses the Liu and Jordan correlation with a validated MBE of 1.7 %. Tests done by the author using the Perez's model produced similar results. Thus by default the software uses the Hay's model with an option of using the Perez-Ineichen model, when high quality diffuse data are available. The model does not address specular reflections as it was deemed by the author not to have negligible energetic consequences (PVSYST 2.0 Manual, 1996).

7.3.1.2 PV model

The software models the PV current using the one-diode Shockley model, with its current expressed as follows:

$$I = I_L - Io \left\{ \exp \frac{q\,(V + IRs)}{N_{cs}\,\gamma\, k\, Tc} - 1 \right\} - \frac{(V + IRs)}{Rsh} \qquad 7.1$$

where

I - current generated by module (A)

V - voltage at module terminals (V)

I_L - photocurrent (A)

Io - diode reverse saturation current (A)

Rs - series resistance (Ω)

Rsh - shunt resistance (Ω)

q - electronic charge = 1.602×10^{-19} C

k - Boltzmann's constant = 1.381×10^{-23} J K^{-1}

γ - curve fitting parameter

N_{cs} - number of cells in series

Tc - effective cell temperature (K)

The above model has been popularly called the five parameter model, namely: the photocurrent I_L, the diode reverse saturation current Io, the series resistance Rs, the shunt resistance Rsh and a curve fitting parameter ($N_{cs}\gamma kTc$). This is similar to the current formulation described in an earlier Chapter. Extracts of some of the components characteristics within the built-in library of PVSYST 2.0 are appended at the end of this thesis (Appendix A.5).

7.3.1.3 Temperature model

It has been explained that the voltage generated by a PV cell has a negative coefficient with increasing temperature of the cells. In this model, the light generated current, I_L dependence on temperature of the PV modules is expressed as follows:

$$I_L = \frac{\Phi}{\Phi_{ref}} \left[I_{Lref} + \mu_{ISC} \left(Tc - Tcref \right) \right] \quad \text{(A)} \qquad 7.2$$

where

Φ and Φ_{ref} - effective and reference irradiances (Wm^{-2})

Tc and Tcref - effective and reference cell temperatures (K)

μ_{ISC} - temperature coefficient of the photocurrent/short circuit current

The default setting within the model assumes PV arrays without back-coverings. The author reported that after adaptation of this model for the integrated installations, the errors for array temperatures over-predictions were from 1 to 4 °C (PVSYST 2.0 manual, 1996).

7.3.2 Execution of PVSYST 2.0

The system requirements for the successful running of PVSYST 2.0 are shown in Table 7.5:

Computer	IBM PC compatible at least 386
Operating system	Windows 3.1 or later
RAM	> 2 MB
Monitor	VGA, SVGA, colour
Floppy disks	3.5 " 1.44 MB
Mouse	required
Co-processor	recommended but not essential
Hard disk	3.5 MB
Printer	every printer supported by Windows

Table 7.5: System requirements to run PVSYST 2.0.

The process of running simulations with PVSYST 2.0 is easiest explained using a flow chart shown in Figure 7.1:

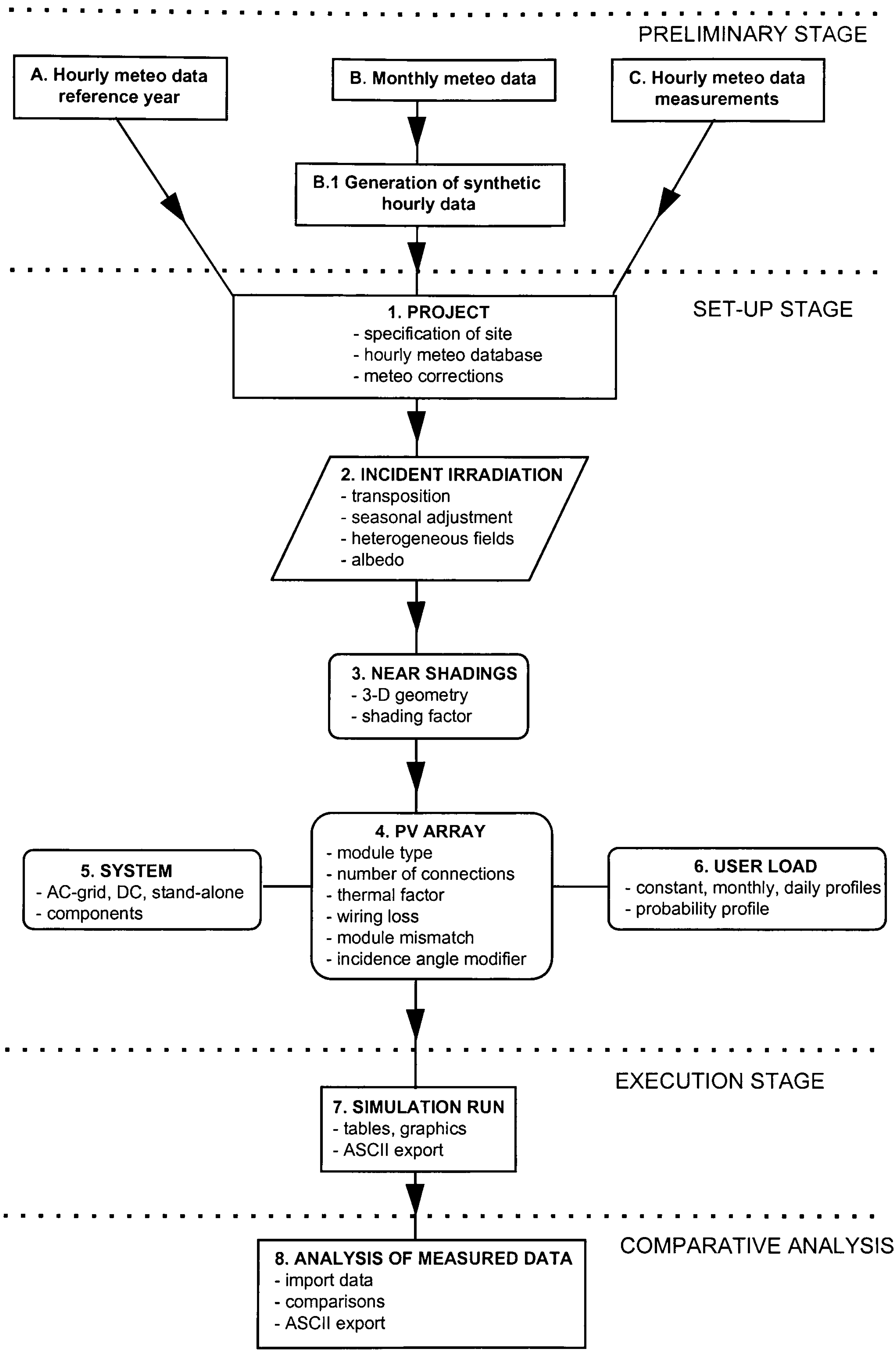


Figure 7.1: Simulation process flow-chart of PVSYST 2.0 (PVSYST 2.0 Manual 1996).

A brief explanation of the flow-chart shown in Figure 7.1 is given as follows:

7.3.2.1 Preliminary stage

The preliminary stage deals with meteorological data input. PVSYST 2.0 processes met data as inputs, obtainable in three ways:

- A - standard hourly met data from reference year.
- B - generation of synthetic met data from mean monthly values.
- C - original measured data from site.

All that is required of A and C is that the data must conform to a certain format requirements. Data for B can be generated from the monthly average values of solar irradiation, the ambient temperature and windspeed.

7.3.2.2 Set-up stage

1. Project

This menu specifies the met data files to the met site. It is a sort of identification so that the software can recognise which file the simulation is for and is to be run at later stages. The importation of met data from A and C is done at this stage. Input into PVSYST 2.0 from one's original measured data can be in hourly as well as sub-hourly intervals, but output from the software are hourly values only. All unfamiliar original met data files must first be transformed into ASCII format so they can be read by the software. After converting, the met values can be examined within PVSYST by viewing the values in tabular or graphical forms.

2. Incident irradiation

The solar irradiance data on the horizontal can be transposed to that of the tilt of the PV panels, taking into considerations seasonal adjustments, heterogeneous fields and the albedo. The software can take only up to two heterogeneously orientated PV panels

3. Near shadings

This part involves the architectural setting-up for the execution of the building integrated PV simulations. Here, the 3-D geometric representation of BiPV arrays are sketched using basic preset drawing tools. This drawing tool includes very basic building structures and shading obstacles that can possibly cast shadows on the PV panels. Theoretically the software caters for any number of PV modules, as long as they are all homogeneously orientated. The values for shading factors can then be calculated and plotted at this stage. This is actually an innovative and a more advanced feature of the software lacking in many others.

4. PV array

In this section, specifications of the PV modules and the wiring system connections are selected. These are all done using a click-menu. Thermal loss, wiring Ohmic losses and cell mismatch are also calculated at this stage. The flexibility of adding more specifications for other PV modules and expanding its library are very innovative and are the more advanced features of the software.

5. System

Here, the BOS system components are input in the software. Various types of system configurations, namely: direct DC, stand-alone and grid-connected are made available. The systems component library has 110 built-in different makes of commercial PV modules and characteristic features, 20 built-in different commercial inverter characteristic features and 71 built-in commercial solar batteries characteristic feature. In addition, there is again the flexibility of adding more system components and batteries if the manufacturer's characteristic data are available at hand. This is also a very advanced feature of the software.

6. User load

This section is the menu for setting the user's load requirements i.e. power demands. It can be input as a constant, i.e. grid-connected, monthly or daily power profiles. Settings for the latter two are at the discretion of the user. Also included is the instantaneous probability profile frequently used for stand-alone systems.

7.3.2.3 Execution stage

7. Simulation run

This part actually starts the execution of the simulation set-up in the software. On-line exportations of various results up to seventy-one types can be invoked here. A variety of graphical outputs can also be commanded at this stage. Results of the simulations can be viewed and analysed at every stage of the way, with a variety of tabular and graphical forms. Finally, all the results of the simulations above can be exported in ASCII format for further analysis and treatment.

7.3.2.4 Comparative analysis

8. Analysis of measured data

This part is very similar to steps 1 through 7 in the preceding paragraphs. The only major difference is that this part has the algorithms for importing and reading one's own measured data i.e. measured met data and the various measured PV data as well. The importation of measured met data means that the data has to be in ASCII format, similar to the preceding simulation part. This part then offers certain comparative analysis of the measured versus simulated data. The measured data can then be visually presented within the software in four major ways using basic graphical comparisons of:

- Basic plot of measured versus simulated data.
- Differences of measured and simulated data as a function of time.
- Ratio of measured to simulated data as a function of time.
- Differences of measured and simulated data as a function of solar time.

This menu also offers the facility of eliminating unwanted data, according to one's desired criteria. All these combinations can be viewed as tabular or graphical values and are exportable into ASCII format for further analysis. This part is again a very uniquely advanced feature of the software compared to the other commercial models.

7.4 Validation of PVSYST 2.0 against the BiPV-WHF system

This section presents and discusses the comparison between results from the monitored data and the simulated results as predicted by PVSYST 2.0.

7.4.1 Simulated overall system performance

A summary of the simulated overall performance as predicted by the PVSYST 2.0 computer model at WHF is shown in Table 7.6:

Month	GlobHor ($kWhm^{-2}d^{-1}$)	T Amb (°C)	TArray (°C)	EOutInv ($kWhd^{-1}kWp^{-1}$)	EffArrR (%)	EffSyR (%)	PR (%)
Jul-96	3.0	10.5	29.0	2.2	10.1	8.9	73.7
Aug-96	3.2	12.4	26.3	2.3	10.1	8.8	72.4
Sep-96	2.4	10.4	19.9	1.8	9.9	8.4	69.7
Oct-96	2.0	7.3	19.1	2.0	10.5	9.2	76.2
Nov-96	0.8	1.9	9.2	0.8	10.0	8.6	71.5
Dec-96	0.4	-0.9	3.6	0.4	8.8	6.9	57.2
Jan-97	0.5	-0.4	6.4	0.3	8.0	6.3	51.9
Feb-97	1.0	2.4	8.2	0.8	9.9	8.2	68.1
Mar-97	2.0	4.8	15.4	1.7	10.6	9.2	76.4
Average	1.7	5.4	15.2	1.4	9.8	8.3	68.5

Table 7.6: Summary of simulated performance results of BiPV-UK at WHF. GlobHoriz - global irradiation on the horizontal; TAmb - measured ambient air temperature; TArray - array temperature; EOutInv - energy output after inverter; EffArrR - efficiency of PV array; EffSyR - efficiency of system; PR - Performance Ratio.

From the values shown in Table 7.6, it can be seen that the global horizontal irradiation ranged from 0.5 to 3.2 $kWhm^{-2}d^{-1}$. The monthly ambient temperature ranged from - 0.9 to 12.4 °C with an average of 5.4 °C. The monthly array temperature ranged from 3.6 to 29.0 °C with a total average of 15.2 °C. The monthly PV output ranged from 0.3 to 2.3 $kWhd^{-1}kWp^{-1}$ and averaged at about 1.4 $kWhd^{-1}kWp^{-1}$. The monthly array efficiency ranged from 8.0 to 10.6 % and averaged at 9.8 %. The monthly system efficiency ranged from 6.3 to 9.2 % and averaged at 8.3 %. The monthly PR ranged from 51.9 to 76.2 % and averaged at 68.5 %.

The outputs discussed in Table 7.6 are graphically represented in Figures 7.2, 7.3 and 7.4:

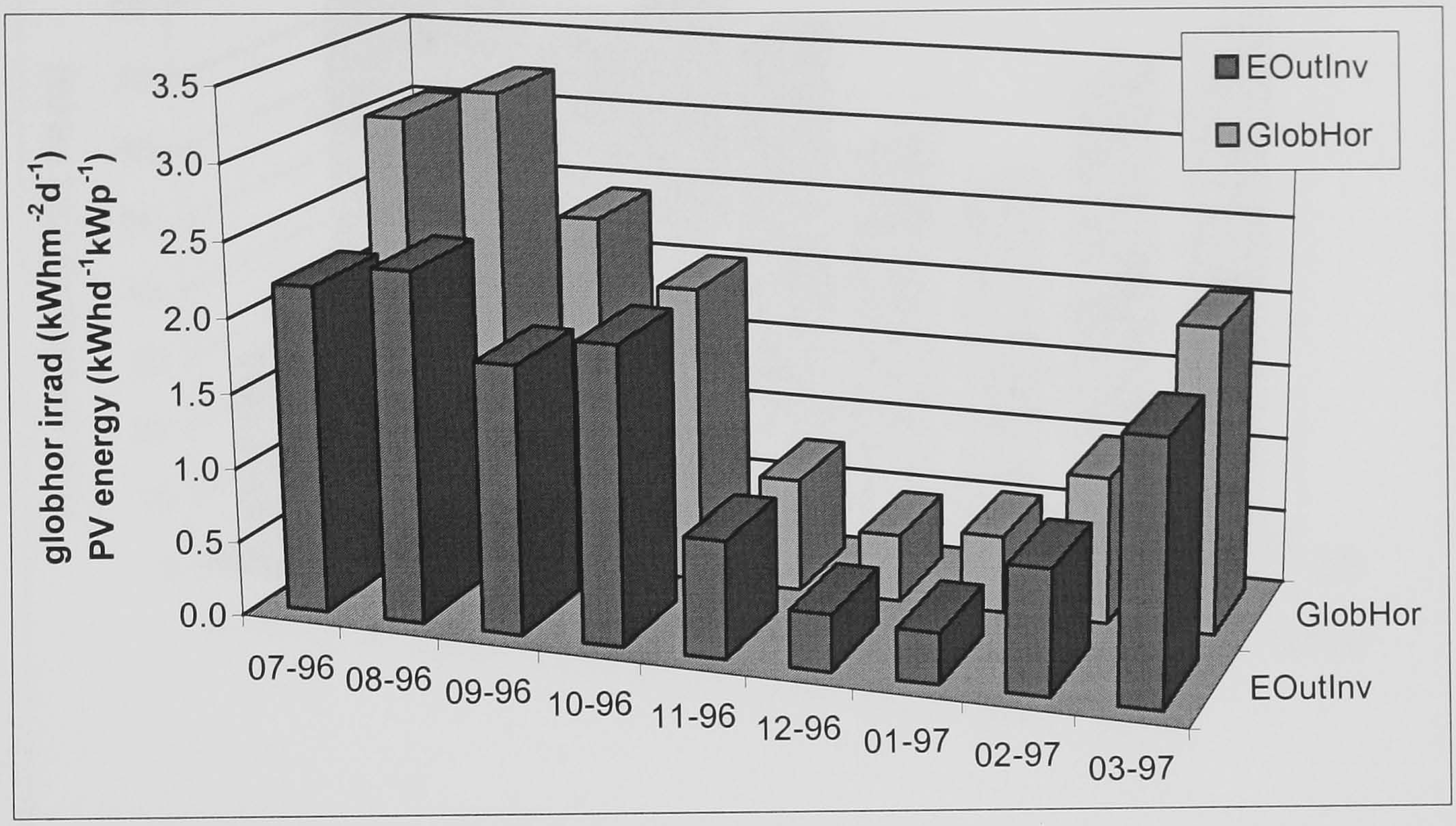


Figure 7.2: Global irradiation and PV energy output as simulated by PVSYST 2.0.

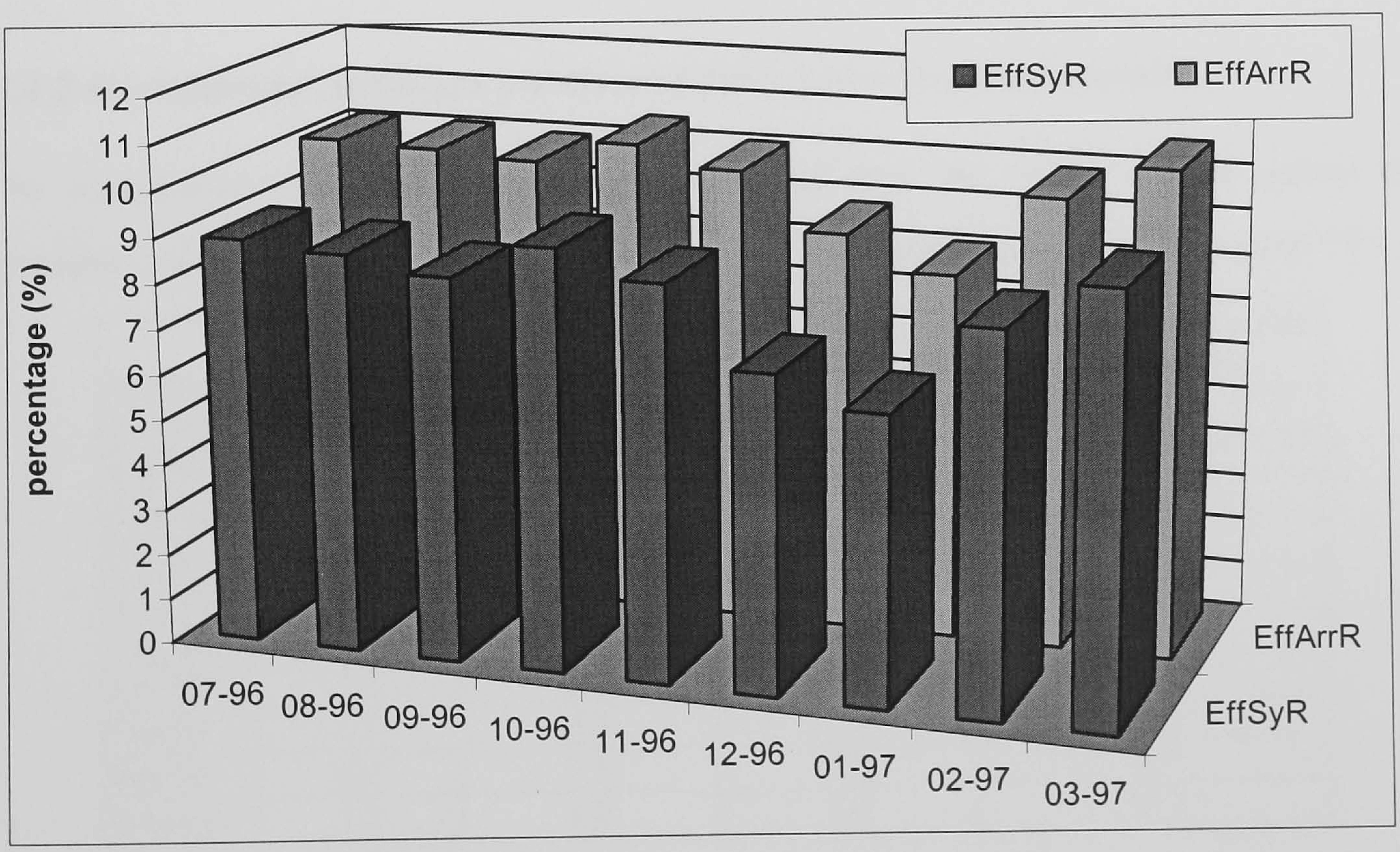


Figure 7.3: Efficiencies and system production as simulated by PVSYST 2.0.

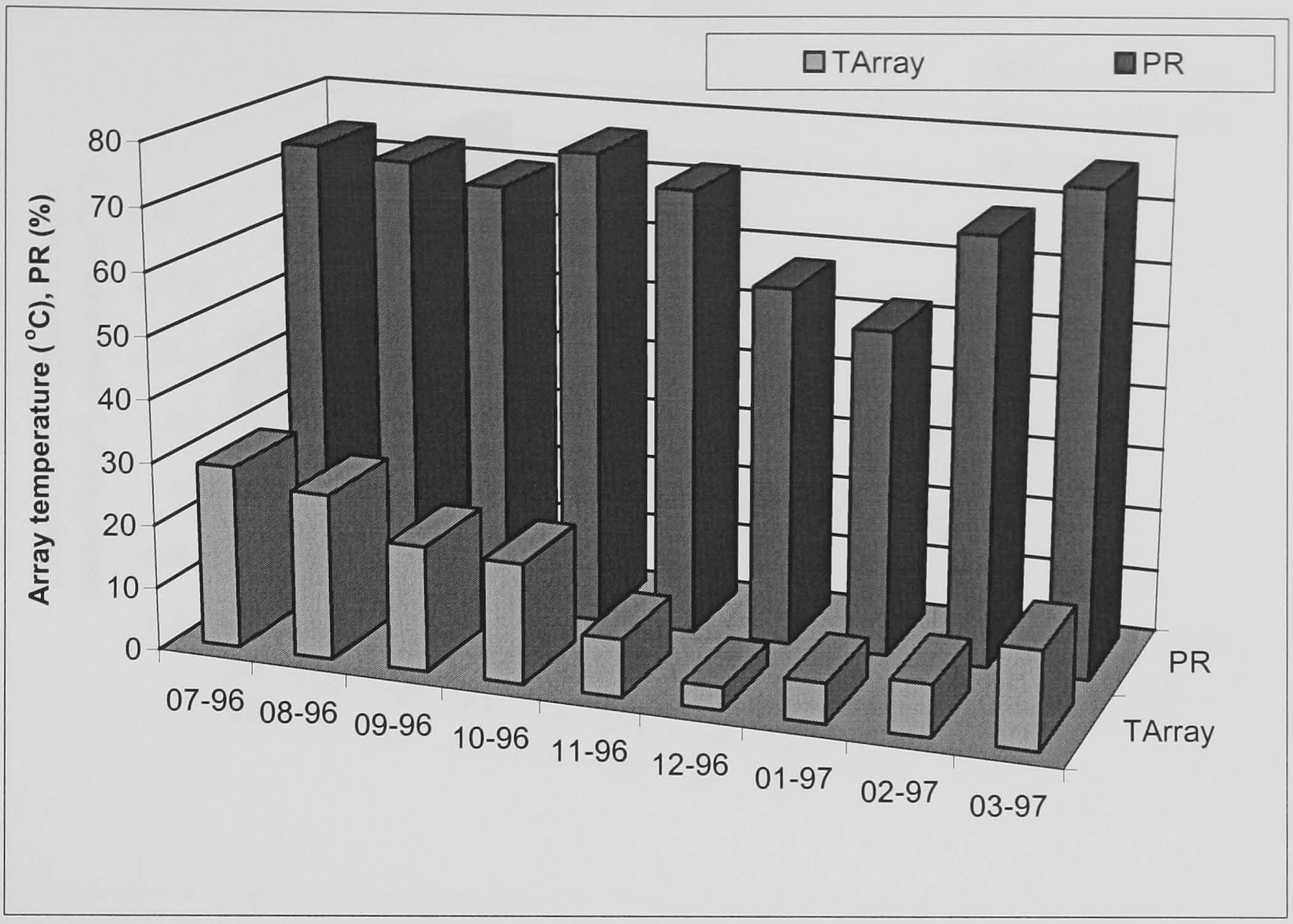


Figure 7.4: Variations of PR with array temperature as simulated by PVSYST 2.0.

7.4.2 Comparison between monitored data and simulated results

The comparative overall performance figures obtained from the monitored data against the simulated results are shown in Table 7.7 and its graphical representation is shown in Figure 7.5:

Month	GlobHor ($kWhm^{-2}d^{-1}$)	Measured yield ($kWhd^{-1}kWp^{-1}$)	Simulated yield ($kWhd^{-1}kWp^{-1}$)	Simulated - Measured difference (%)
Jul 96	3.0	2.1	2.2	5.0
Aug 96	3.2	2.0	2.3	15.6
Sep 96	2.4	1.4	1.8	24.4
Oct 96	2.0	1.3	2.0	45.0
Nov 96	0.8	0.7	0.8	6.7
Dec 96	0.4	0.3	0.4	33.3
Jan 97	0.5	0.3	0.3	-1.1
Feb 97	1.0	0.7	0.8	11.6
Mar 97	2.0	1.8	1.7	-3.1
Average	1.7	1.2	1.4	15.3

Table 7.7: Comparative overall system performance for WHF from monitored data and simulated results. Positive indicates software over-prediction.

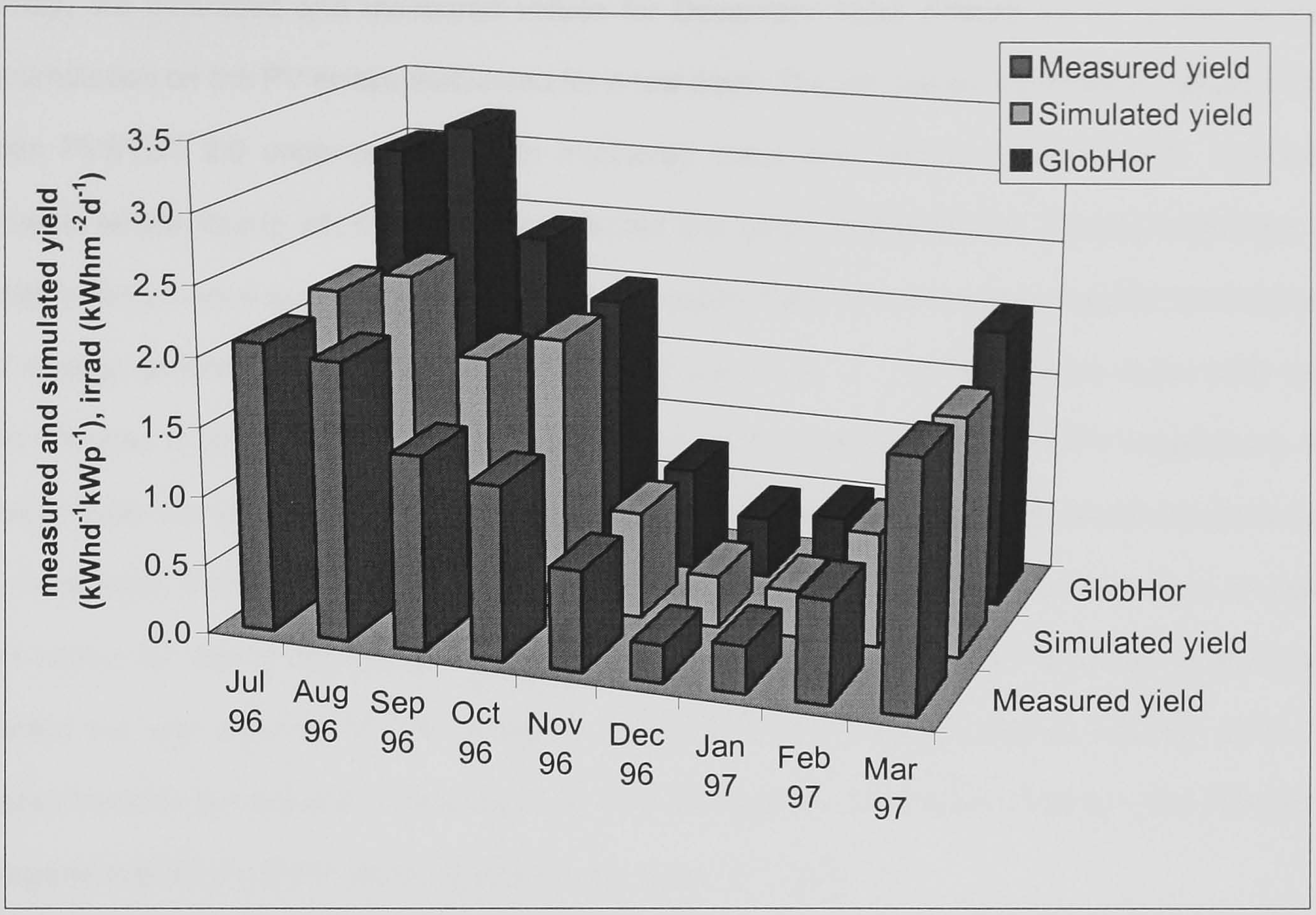


Figure 7.5: Graphical representation of overall performance from monitored and simulated values.

From the monthly global AC values shown in Table 7.7, and in Figure 7.5, it can be seen that basically, the computer model PVSYST 2.0 performed variations of simulations from an under-prediction of 1.1 % to an over-prediction of up to 45 %, with an average over-prediction of 15.3 %. The author reported a monthly global AC simulation output with a possible MBE under-prediction of 12.8 % to an over-prediction of 5.5 %. This anomaly is attributed to several major reasons.

Firstly, it lies in the difficulty of modelling such a unique design as the BiPV-WHF installation, with shading of the panels which has been discussed in an earlier Chapter.

Secondly, the WHF system has been suffering from an incompatible EPROM window built-in the inverter since commissioning up to the month of November 1996, which gave PVSYST 2.0 an impossible task of accomplishing. This explains the over-predictions from July 1996 through to November 1996, when the new EPROM was finally installed.

Thirdly, the simulated and measured values for December 1996 differed by 33 % due to snow accumulation on the PV arrays that lasted for a few days. The simulation improved in January 1997, when PVSYST 2.0 under-predicted the monitored value only slightly at about 1 %. The lower ambient temperatures seemed to have affected the panel temperatures, thereby improving the system performance generally. In February 1997, again there was snow accumulation that hindered PV energy generation, thus giving rise to an over-prediction of 11.6 %. A more reasonable value was obtained in March 1997, when the climate was deemed as optimum for BiPV installations, with clearer skies and nearer to optimum temperatures. This is shown by an under-prediction of about 3 %. In general, the actual BiPV array temperatures have been higher than as had been expected and hoped for during the design stage. It seems to have benefited the PV panels in the colder months but with adverse effects during the warmer months. The "excessive heating" of the PV arrays lowered the system performance as was discussed in an earlier Chapter. The peak array temperatures for the BiPV-WHF installation are shown in Table 7.8:

Month	T_a	T_m	I_m	U_m	T_s	I_s	U_s	% T_s-m	% I_s-m	% U_s-m
Jul 96	34.0	64.0	0.8	292.0	48.0	3.1	281.3	-28.6	117.9	-3.7
Aug 96	22.2	56.1	0.1	290.0	44.4	1.7	289.0	-23.3	177.8	-0.3
Sep 96	24.7	49.8	0.2	297.0	43.4	6.5	287.5	-13.7	188.1	-3.3
Oct 96	17.5	45.0	4.9	270.5	41.5	10.1	276.9	-8.1	69.3	2.3
Nov 96	12.7	29.2	4.2	267.0	19.2	4.2	292.5	-41.3	0.0	9.1
Dec 96	2.3	19.9	2.8	250.0	8.1	3.7	295.3	-84.3	27.7	16.6
Jan 97	7.0	31.2	4.1	268.0	19.3	4.6	295.0	-47.1	11.5	9.6
Feb 97	7.7	31.3	4.8	265.0	15.2	5.0	291.6	-69.2	4.1	9.6
Mar 97	20.4	43.1	6.1	239.0	36.1	6.4	294.8	-17.7	4.8	20.9
Ave p.a.	16.0	41.1	3.1	270.9	30.6	5.0	289.3	-29.3	47.2	6.6

Table 7.8: Peak array temperatures and average DC output performances. T - temperature; I - array current; U - array voltage; a - ambient; m - monitored; s - simulated.

Clearly, from the values shown in Table 7.8, it can be seen that the peak array temperatures have been much higher than the ambient temperatures. The peak array temperature was measured to be 64.0 °C in July 1996, whence the simulated value was 48.0 °C with an ambient of 34 °C. This represents an under-prediction of 28.6 %. In December 1997, the measured array temperature peaked at 19.9 °C whence the simulated array temperature was 8.1 °C with an ambient of 2.3 °C. This represents an under-prediction of 84.3 %. The patterns are similar with all the other months and thus it can be said that PVSYST 2.0 generally under-predicted the array temperatures from 8.1

to 84.3 % with an average of 29.3 %. Figure 7.6 shows the graphical illustration of the temperatures.

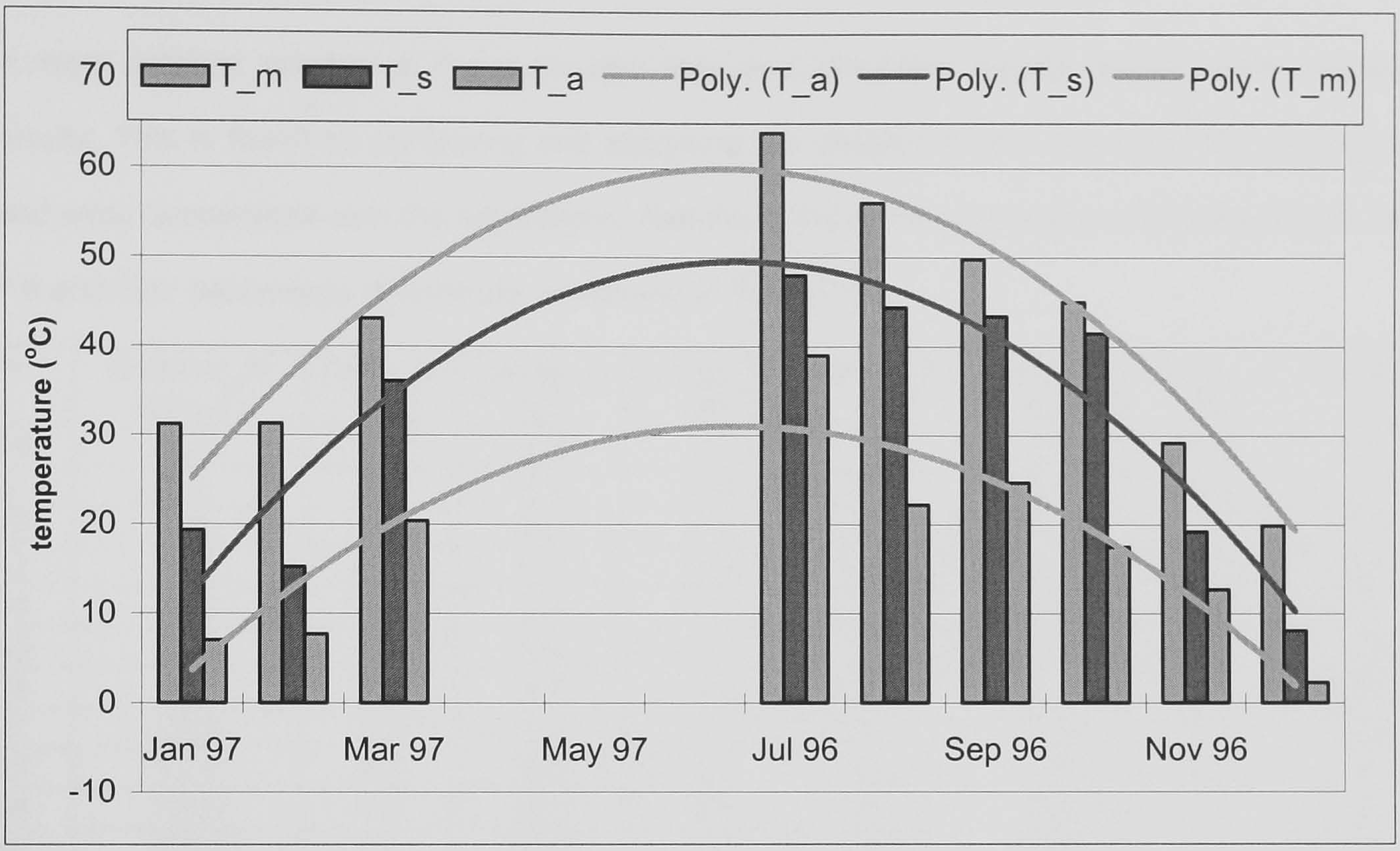


Figure 7.6: Peak array temperature for BiPV-WHF installation. Poly - shows the interpolated ambient and array temperatures using a polynomial fit for a year.

From the average monthly values of current and voltages shown in Table 7.8, it can be seen that PVSYST 2.0 under-predicted heavily from -188 to 0 %. However, this value included the trippings of the voltage fault from the original EPROM setting. Then, with the correct EPROM setting, the model over-predicted the array current by up to 27.7 % with an average of 9.6 % overall. The voltage values were predicted as closer to the monitored values with the original EPROM. However, the model over-predicted from 9 to 21 % with an average of 13.2 %, after the new EPROM was installed. Thus it can be seen that the repercussions of the shading effects, initial EPROM incompatibility, snow and elevated array temperatures resulted in the grave perturbation of the DC output of the arrays.

Thus, from results of the comparative study for the BiPV-WHF installation, it can be said that PVSYST 2.0 generally over-predicted the global AC output by about 15.3 %, the array current by about 9.6 % and the array voltage by about 13.2 %.

7.4.2.1 Hourly DC performance and hourly array temperature

A more detailed scrutiny of the measured data and simulated results reveals quite interesting results. This is found by comparing and analysing the detailed hourly monitored DC performance and array temperature with the simulations. Results of these are juxtaposed and presented in Table 7.9 and their percentage differences are shown in Table 7.10:

Hr	Globhor_m (Wm-2)	Tamb_m (C)	Tarray_m (C)	Iarray_m (A)	Uarray_m (V)	Tarray_s (C)	Iarray_s (A)	Uarray_s (V)
00	0.0	3.6	4.3	0.0	0.0	4.6	0.0	0.0
01	0.0	3.5	4.3	0.0	0.0	4.5	0.0	0.0
02	0.0	3.7	5.0	0.0	0.0	4.7	0.0	0.0
03	0.0	3.4	5.1	0.0	0.0	4.5	0.0	0.0
04	0.0	3.5	4.9	0.0	0.0	4.5	0.0	0.0
05	0.0	3.4	4.6	0.0	0.0	4.5	0.0	0.0
06	4.7	3.5	4.9	0.0	50.9	4.7	0.0	28.6
07	23.9	3.7	6.1	0.1	111.6	5.2	0.1	99.8
08	71.9	4.8	8.8	0.5	166.4	6.8	0.4	155.1
09	113.5	4.6	10.0	0.9	240.8	7.5	0.9	227.2
10	195.8	6.4	16.1	1.7	265.9	10.5	1.7	277.3
11	242.7	7.6	19.9	2.2	265.1	13.2	2.4	278.9
12	262.6	8.5	22.3	2.3	265.5	14.8	2.7	275.1
13	258.2	9.0	23.6	2.3	264.9	15.1	2.5	275.0
14	232.5	9.3	23.1	2.1	261.9	14.9	2.3	272.0
15	176.7	8.7	20.6	1.4	263.5	13.2	1.6	272.9
16	123.5	7.9	17.6	0.8	263.7	11.5	1.0	266.7
17	70.3	6.8	13.5	0.4	206.3	9.2	0.5	177.2
18	32.1	6.1	9.1	0.1	131.9	7.9	0.2	122.0
19	12.2	5.2	6.7	0.0	80.8	6.7	0.1	70.6
20	1.9	4.8	5.6	0.0	40.6	6.0	0.0	31.3
21	0.0	4.3	5.0	0.0	6.7	5.4	0.0	11.6
22	0.0	4.1	4.9	0.0	0.0	5.2	0.0	0.0
23	0.0	3.9	4.7	0.0	0.0	4.9	0.0	0.0
Ave	121.5	5.4	10.4	1.2	170.4	7.9	1.3	167.3

Table: 7.9: Hourly monitored and simulated values from July 96 - March 97. Iarray - array current; Tarray - array temperature; Uarray - array voltage; _m - measured data; _s - simulated results.

Hr	Is-Im (A)	Us-Um (V)	Ts-Tm (C)	Is-Im (%)*	Us-Um (%)*	Ts-Tm (%)
00	0.0	0.0	0.3	0.0	0.0	5.9
01	0.0	0.0	0.2	0.0	0.0	4.1
02	0.0	0.0	-0.3	0.0	0.0	-5.9
03	0.0	0.0	-0.6	0.0	0.0	-12.5
04	0.0	0.0	-0.4	0.0	0.0	-8.7
05	0.0	-6.7	-0.2	0.0	0.0	-3.4
06	0.0	-22.2	-0.3	0.0	-55.9	-5.5
07	0.0	-11.9	-0.9	-19.5	-11.2	-15.4
08	-0.1	-11.3	-2.0	-14.3	-7.0	-25.8
09	0.0	-13.5	-2.4	5.1	-5.8	-27.9
10	0.0	11.4	-5.5	0.1	4.2	-41.6
11	0.3	13.9	-6.7	11.6	5.1	-40.4
12	0.4	9.6	-7.6	16.2	3.5	-40.8
13	0.2	10.0	-8.5	8.9	3.7	-44.1
14	0.2	10.1	-8.2	8.0	3.8	-43.2
15	0.2	9.4	-7.4	15.0	3.5	-44.1
16	0.2	3.0	-6.1	25.8	1.1	-42.2
17	0.1	-29.1	-4.3	18.0	-15.2	-37.6
18	0.1	-9.9	-1.2	57.3	-7.8	-14.2
19	0.0	-10.3	0.0	37.0	-13.6	0.1
20	0.0	-9.3	0.4	0.0	-25.8	7.1
21	0.0	5.0	0.4	0.0	54.4	8.5
22	0.0	0.0	0.3	0.0	0.0	5.2
23	0.0	0.0	0.3	0.0	0.0	5.7
Ave	0.1	-0.7	-2.5	10.8	-0.3	-27.6

Table 7.10: Percent difference between monitored and simulated values. _m - measured data; _s - simulated results. * average values for current and voltage considered only from 0700 to 1900 hours, i.e. excluding grazing irradiances. Positive indicates over-prediction.

Hourly DC performance

From the results shown in Tables 7.9 and 7.10, the hourly monitored data show an average array current of 1.2 A DC against a predicted 1.3 A DC during operating hours for the whole duration of the logging. When neglecting grazing irradiances in the early morning and late evening, i.e. taking the values from 0700 till 1900 hours, PVSYST 2.0 seems to over-predict the array current by about 10.8 % difference. The hourly monitored array voltage gave an average of 170.4 V DC while the model under-predicted the array voltage at 167.3 V DC. Again, when neglecting grazing irradiances this gave an under-prediction by about 0.3 %. The hourly DC energy simulation reported by the author showed a possible hourly RMSE over-prediction between 5.2 to 17.7 %. In summary, this means that PVSYST 2.0 over-predicted the hourly DC array current by 10.8 % and under-predicted the hourly array voltage by 0.3 %. This is well within the anticipated validation report as published by the author with an RMSE over-prediction of 5.2 % to 17. 7 %. These averaged hourly values for array current and voltage are shown in Figures 7.7 and 7.8:

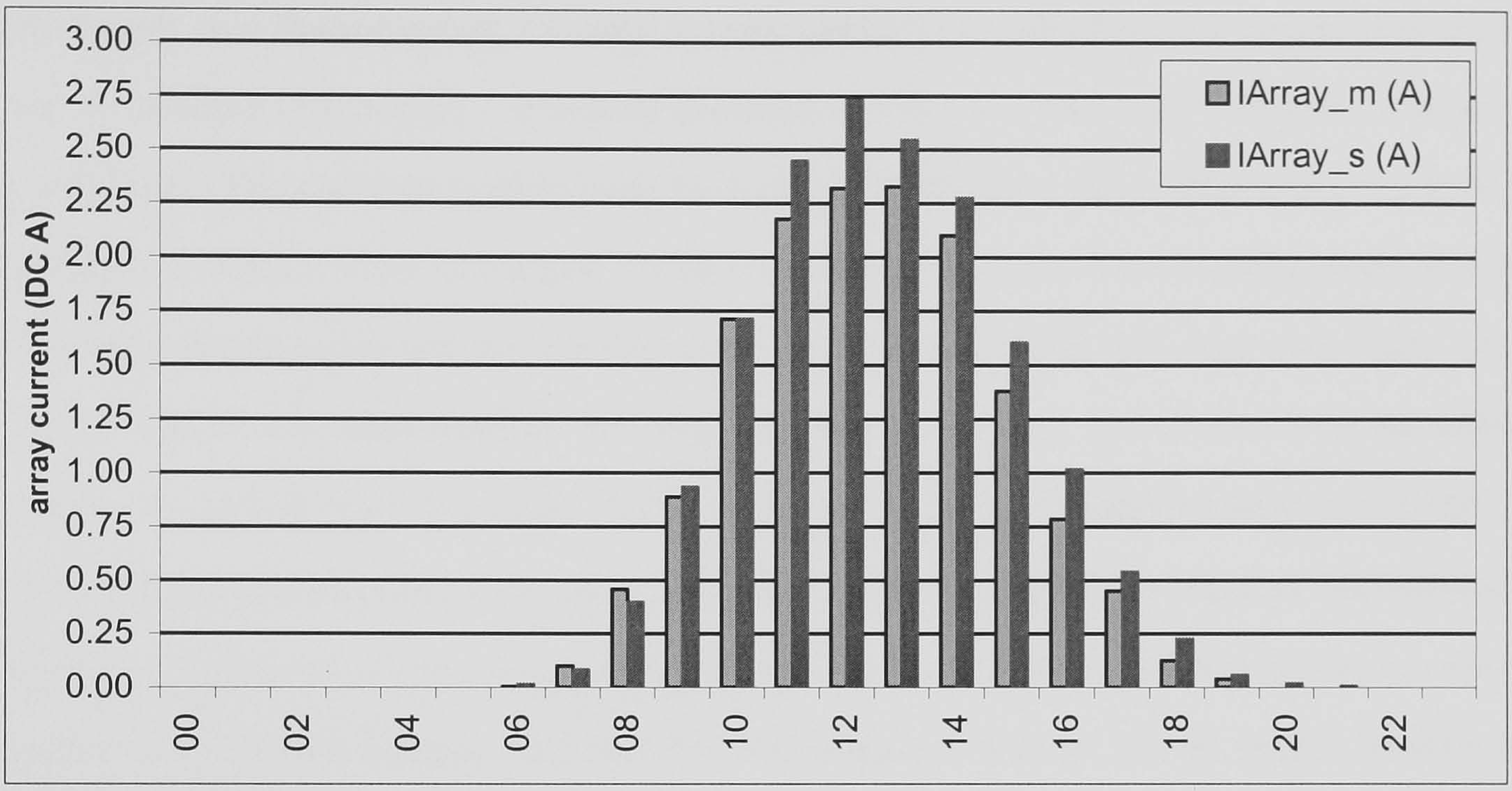


Figure 7.7: Hourly values of measured and simulated array currents.

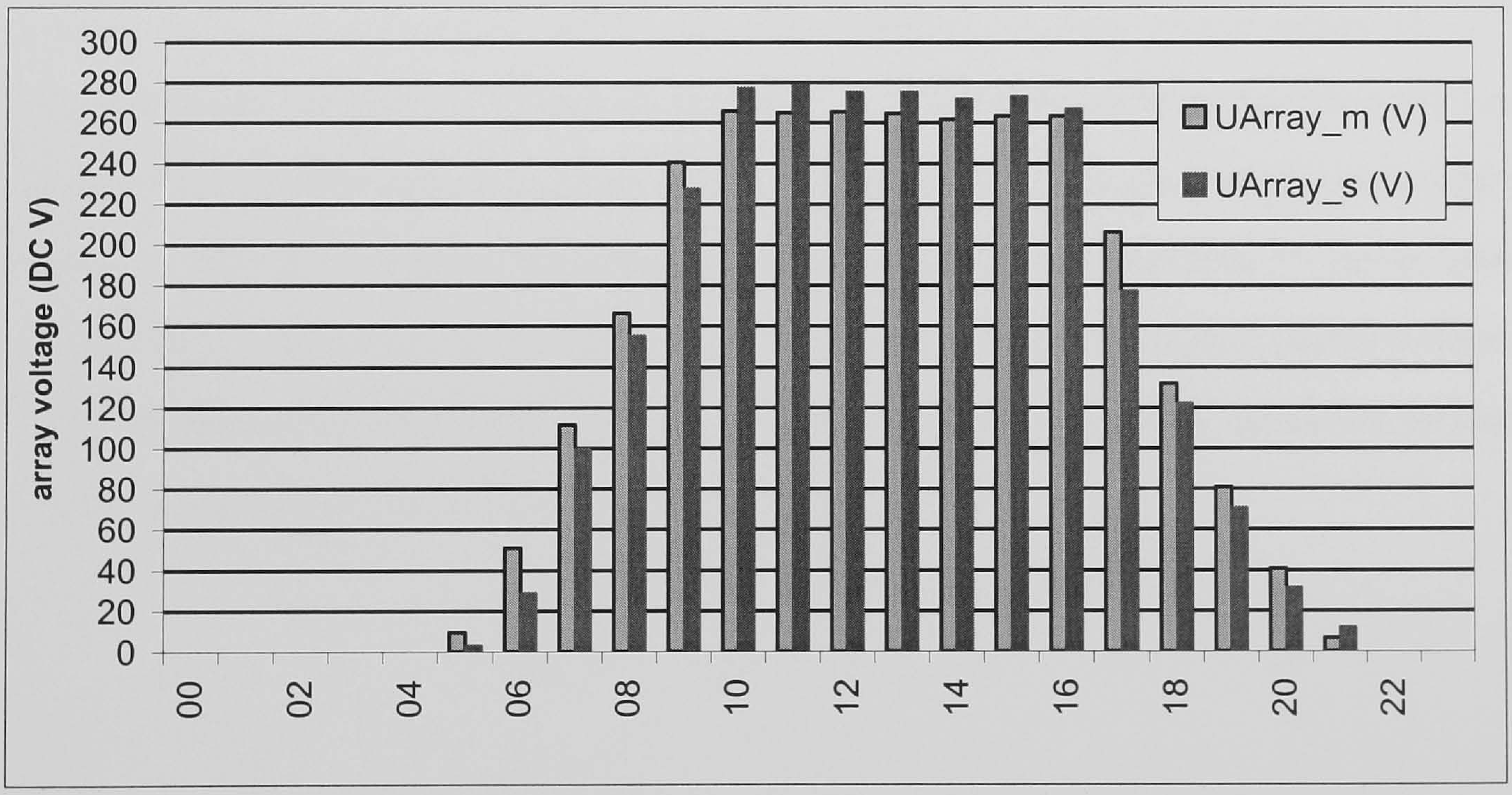


Figure 7.8: Hourly measured and simulated array voltages.

Hourly array temperature

The results shown in Tables 7.9 and 7.10 indicate that the array temperatures have been significantly under-predicted by the simulation with a difference of 27.6 °C for the whole duration of the logging, in a 24 hour period. It tended to under-predict the night-time array temperature slightly with a difference of less than 1 % outside the hours of 0700 till 1700 hours. However, it tended to under-predict the operating daytime array temperature significantly with a difference of up to 44 % as shown in Table 7.10 at 1500 hours. All the monitored hourly data and simulated results in Table 7.10 show similar trends with the monthly values as discussed earlier with regards to Table 7.8, in which PVSYST 2.0 under-predicted the measured data from about 13.7 to 28.6 % in the warmer months, to up to 84.3 % in the colder months. Again this is due to the default setting in PVSYST 2.0 that uses the ambient temperature as its basis of calculations. Due to the negative dependence of PV output on the rise in array temperature, this elevated array temperature due to it being used as roofing of the heated walkway has not been addressed by PVSYST 2.0 by default. Besides the EPROM incompatibility, this temperature issue seems consistent with the same main reason the software over-predicted the global AC outputs by about 15 % despite after having over-predicted the hourly DC array currents by 10.8 % and under-predicted the array voltage slightly by 0.3 %. This large hourly temperature under-prediction of 16 °C, is significantly higher than the hourly array temperature simulation reported by the author, which showed a possible RMSE over-prediction between 1.5 to 3.8 °C. However, the author's simulated values were defaulted for PV panels without back-coverings, thus justifying the behaviour of these predictions. The scatter diagrams showing these elevated array temperatures due to the heating regimes of the walkway against the simulated array temperatures are shown in Figures 7.9a and 7.9b:

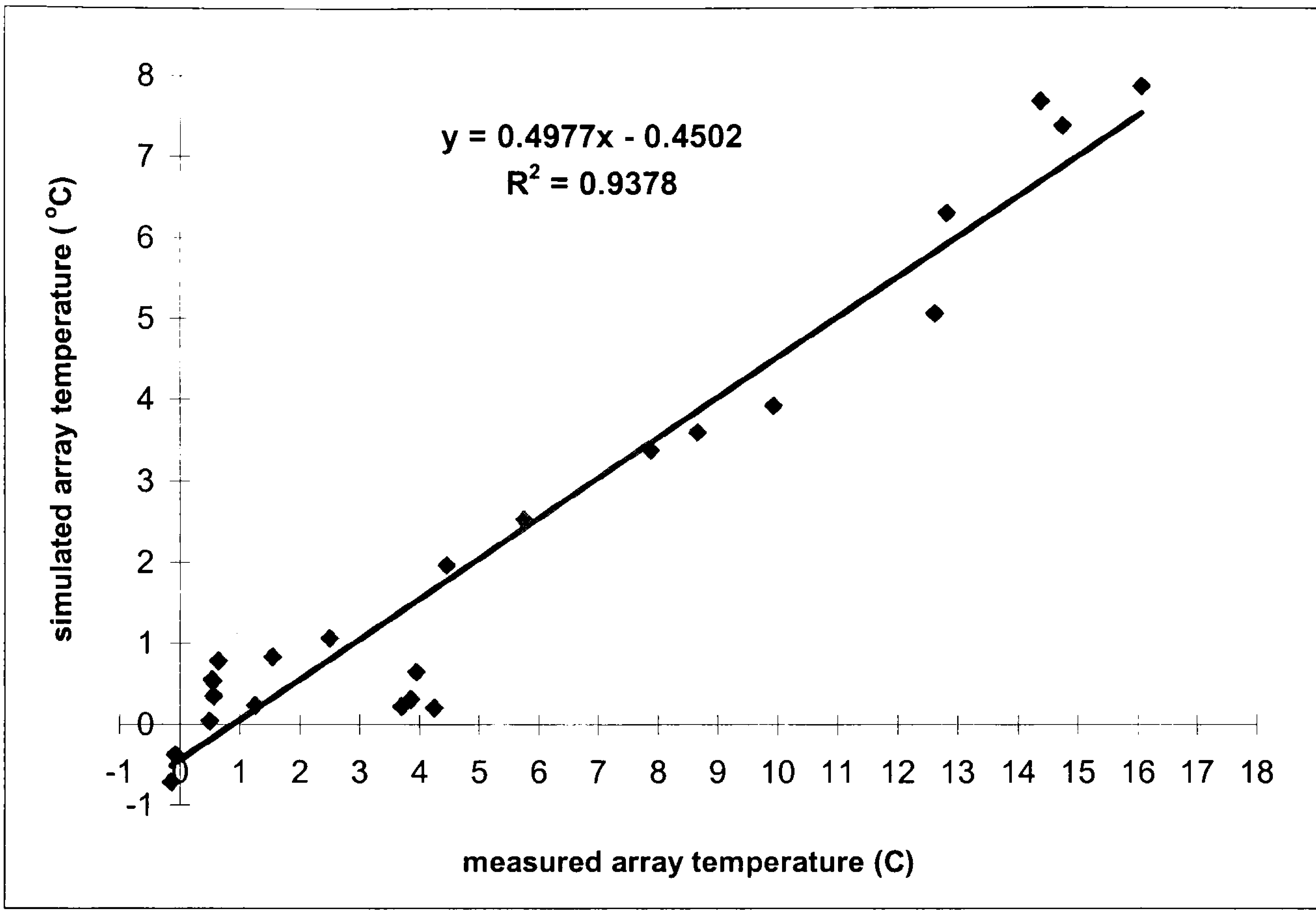


Figure 7.9a: Scatter plot of hourly measured and simulated array temperatures for January 1997.

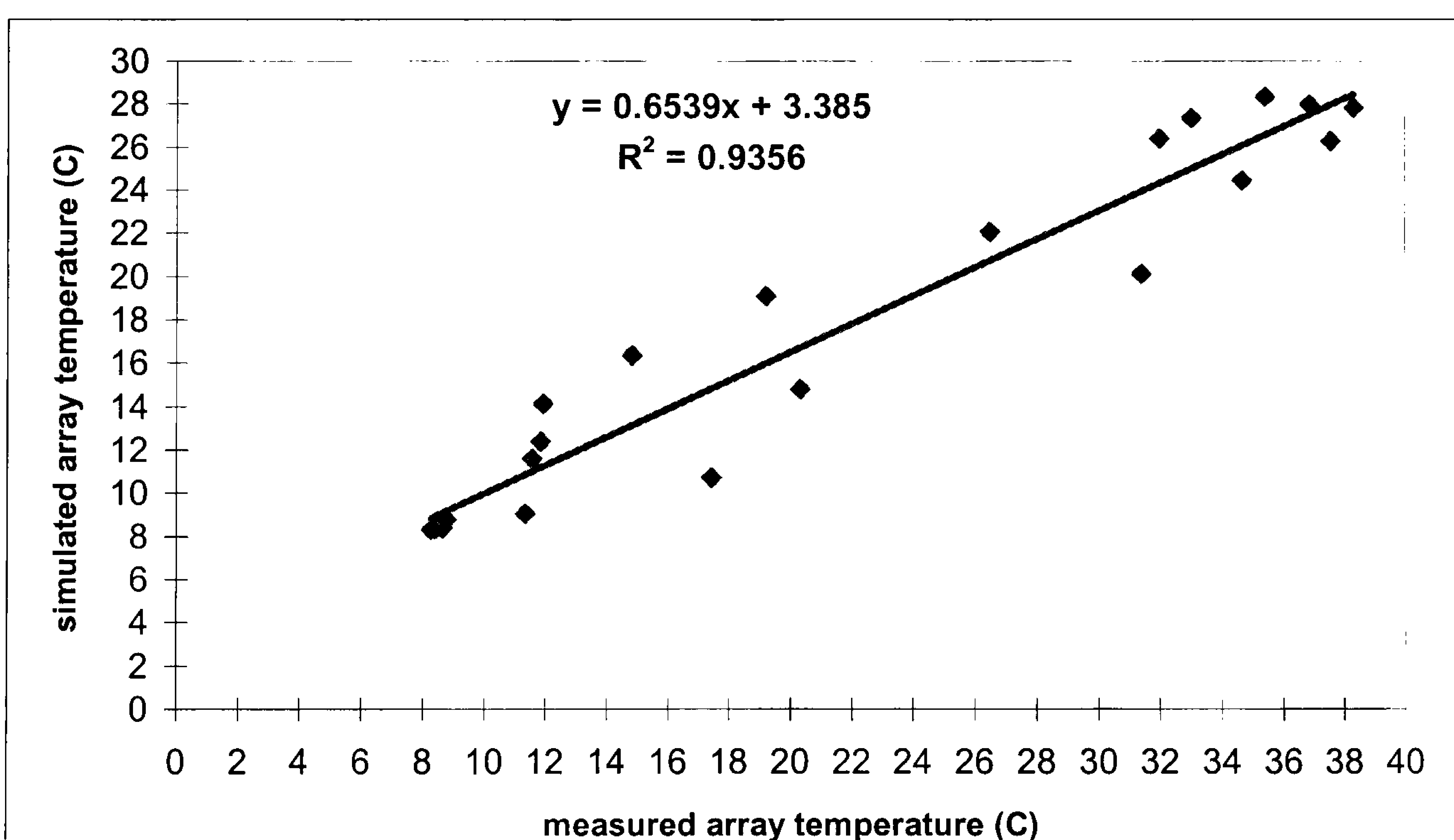


Figure 7.9b: Scatter plot of hourly measured and simulated array temperatures for July 1996.

Figures 7.9a and 7.9b show the scatter charts for the BiPV-WHF site for January 1997 and July 1996 respectively. Both charts show that the measured array temperatures are always higher than the simulated array temperature. This is due to the heating regime in the Winter months and latent heat gains in the other months at the WHF office. Again this means that the PVSYST 2.0 default in simulating BiPV arrays without back coverings, despite after making adaptations for the integrated installations, tended to under-predict the array temperatures, thereby over-predicting the system performance for the BiPV-WHF installation. Scatter plots for other months showed similar trends and are appended at the end of this thesis (Appendix A.6).

This means that for other real site-specific BiPV installations, the operating array temperatures when they are being integrated into buildings have to be taken into account in future PVSYST 2.0 simulation set-ups. In other words, the thermal aspects for a particular BiPV site and building specifics, that may alter the base air temperature for the PV arrays must first be considered, either through measurements, or through simulations using building thermal engines. These elevated air temperatures behind the back of the PV arrays, instead of the true ambient air temperatures, can then be used as input in the setting-up of PVSYST 2.0 as a means to enhance its predictions. As such, the final predictions using PVSYST 2.0 will only then, be based upon more realistic thermal features of the site and building specifics of a particular BiPV installation. This finding is in tandem with other published work in the area (Brinkworth *et.al.*, 1997; Clarke *et.al.,* 1997; King, 1997; Hankins, 1995; Mosfegh and Sandberg, 1995; Markvart, 1994; Groehn, 1993, Strong and Scheller, 1993, Overstraeten and Mertens, 1986, Twidell and Weir, 1986, Green 1982, Palz 1978). This effect has been observed in the Australian BiPV installation which have incorporated ventilation designs for controlling the array temperatures.

A graphical representation of the average hourly array temperature as discussed for the BiPV-WHF installation in this section, for the whole duration of the logging is shown in Figure 7.10 and the hourly percentage differences of the array current, voltage and temperatures are graphically illustrated in Figure 7.11:

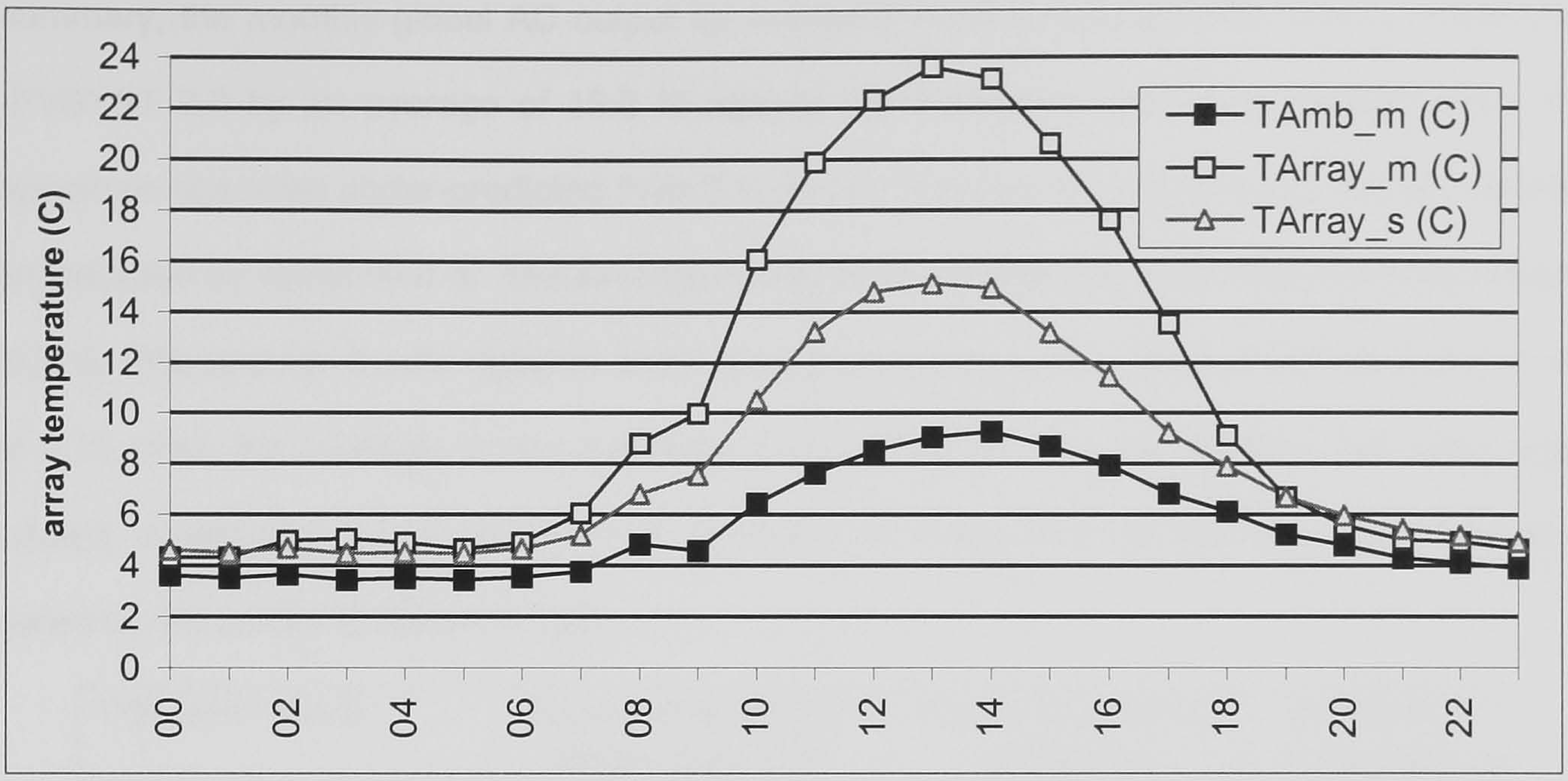


Figure 7.10: Hourly ambient, measured and simulated array temperatures at WHF site over the period of monitoring.

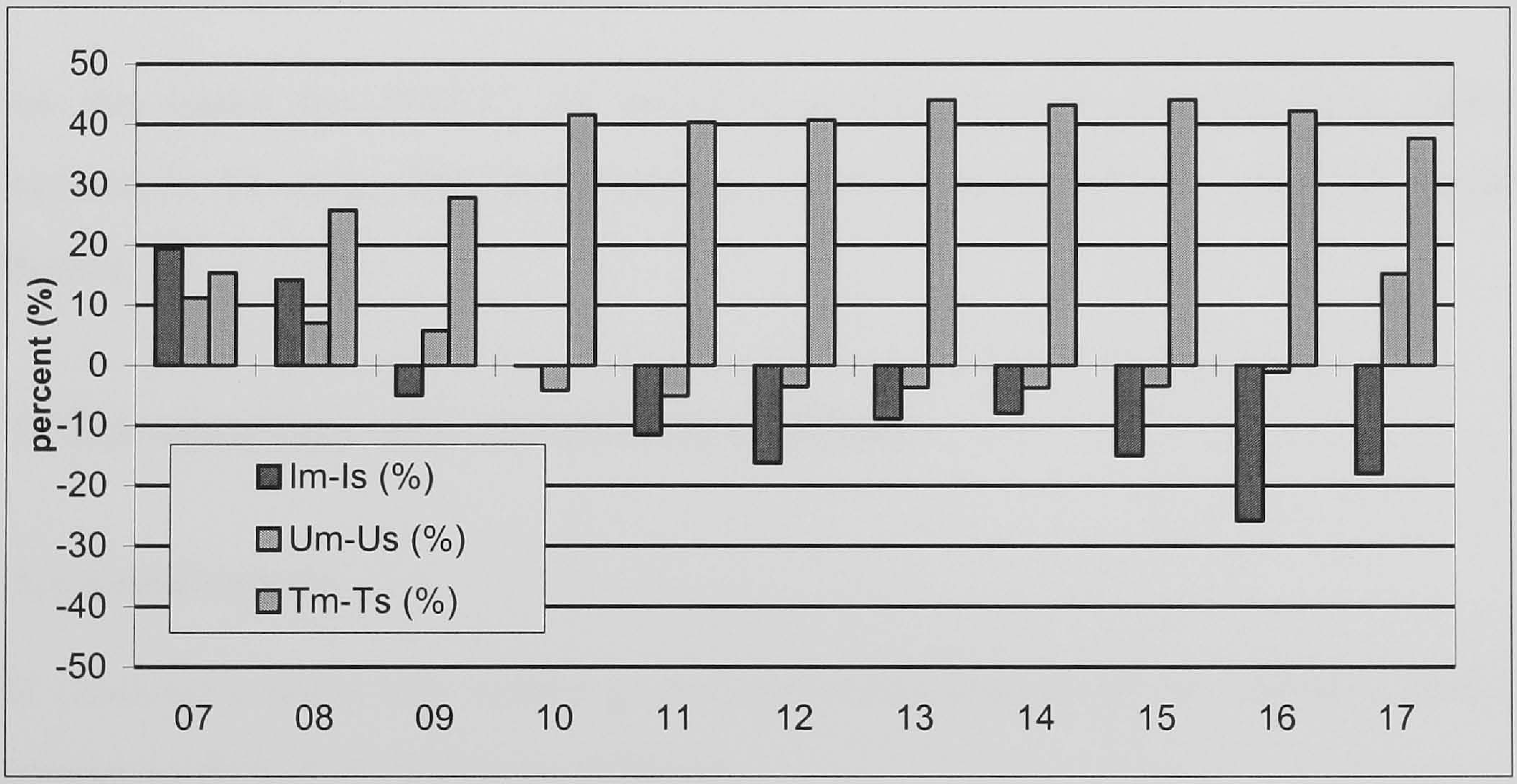


Figure 7.11: Percent difference between measured and simulated values.

Figure 7.10 shows the average hourly differences between the measured data and the simulated results. It is clear that the under-prediction is significant, exacerbated by the heating regime for the WHF installation in the colder months. Figure 7.11 shows the overall percent differences in the hourly array currents, voltages and temperatures against the simulated values, with the under-prediction of the hourly array temperatures as being the dominant one.

In summary, the monthly global AC output for the BiPV-WHF installation has been over-predicted by PVSYST 2.0 by an average of 15.3 % against the monitored data. The monthly peak array temperature has been under-predicted from 8 to 84 %. The average hourly array current has been over-predicted by about 10.8 %. The average hourly array voltage has been slightly under-predicted by 0.3 %. The average hourly nightime array temperature has been slightly under-predicted by less than 1 % while the average hourly operating array temperature in the daytime has been under-predicted significantly by up to 44 %. A summary of these findings and the validation results reported by the author is shown in Table 7.11:

Validation mode	Hourly array RMSE temperature (^{o}C)	Hourly DC RMSE output (%)	Global AC output (%)
PVSYST 2.0 Manual	1.5 to 3.8	5.2 to 17.7	-12.8 to 5.5
BiPV-WHF results	- 8.5 to 0.3	-0.3 to 19.5	15.3

Table 7.11: Summary of validation results by author and findings from the BiPV-WHF installation. Positive indicates over-prediction.

Thus, this means that PVSYST 2.0 performed simulations within an encouraging range of accuracies for the unique BiPV-WHF installation, in restrospect of inherent design and operating difficulties.

7.5 Conclusions and recommendations

7.5.1 Conclusions

The conclusions drawn with regards to the comparative analysis of the monitored data and simulated results by PVSYST 2.0 are as follows:

1. The computer model generally over-predicted the AC outputs from the WHF installation. PVSYST 2.0, in using the default setting, over-predicted the AC global output by 15.3 % against an MBE under-prediction of 12.8 % to an over-prediction of 5.5 % as reported by the author.

2. The computer model was indeed capable of simulating BiPV performances for the WHF installation. However, the error margins found for the BiPV-WHF installation was wider than the

anticipated ones as reported by the author with regards to the DC energy output. PVSYST 2.0 over-predicted the hourly array current by 10.8 % and under-predicted the hourly array voltage by 0.3 %. The reported RMSE hourly values for the DC output as reported by the author was an over-prediction of 5.2 to 17.7 %. This seemed to be within an encouraging range of accuracies especially considering the site's inherent design and operating difficulties.

3. The original EPROM installed in the inverter gave problems that could not have been simulated by PVSYST 2.0, since it was a fault within the hardware. Thus the values of current, voltage and consequently the global output could not have been predicted comfortably and precisely by PVSYST 2.0 under normal circumstances.

4. The computer model predicted nightime array temperature with an under-prediction of less than 1 %, which is very close to the anticipated errors as reported by the author. However, PVSYST 2.0 under-predicted the hourly daytime array temperatures significantly by an under-prediction of up to 8.5 °C. The reported RMSE hourly values for the array temperatures was an over-prediction of 1.5 to 3.8 °C. Thus it is seen that the default setting in PVSYST 2.0 with regards to the array temperature calculations produced significant differences between the measured data and simulated results. Consequently, PVSYST 2.0 over-predicts the system performance by assuming a lower module temperature for its calculations. It seemed that the model would need an enhancement tool for the thermal simulations for its temperature of the array calculator to overcome this situation.

5. The findings with regards to the inverter faults and the higher array temperatures were exacerbated by the unique design of the BiPV-WHF installation. The building architecture did not offer an optimum design to obtain a maximum output from the integrated PV modules, in alleviating or minimising shading of the modules. All these factors produced over-predictions of the simulated performances.

6. PVSYST 2.0 was generally found to be highly flexible, very portable, reliable and relatively user-friendly. It was able to model quite complex BiPV installations as shown by the comparative results from the WHF installation. It showed promise in its widespread use at the scientific and engineering research level and was deemed very suitable for use in the later stages of this research project.

7.5.2 Recommendations

It took about four complete months to learn PVSYST 2.0 to reach an effective level. This was to reach a stage where the user could start from scratch, understand how it worked, set-up and execute the simulations as well as the comparative executions. The experience gained from this comparative work was in some ways a weak parallelism to an independent review, which found that PVSYST 2.0 was a comprehensive tool but required considerable PV and computing expertise (ETSU, 1997). An earlier version of the software called PVSYST 1.0 had been made available in the open market since 1991. This was been tested and was upgraded thereby producing this more advanced version as PVSYST 2.0. This later version seems to be very suitable for the intended use, but not without imperfections.

The apparent limitations and problems of the PVSYST 2.0 software are:

- The software gives output only in hourly values, although input may be sub-hourly.
- The software does not provide viewing, analysing outputs and exporting facilities for intervals of electric power directly, although this was not crucial as it could be easily calculated from the current and voltage values at any time.
- There have been several minor bugs experienced in the English version of PVSYST 2.0 but fortunately, those did not affect the desired calculations.
- The source code for the program is not available for any treatment.
- There was no support group for users. All queries have to be referred directly to the author for technical support.

Based on the experienced gained in using PVSYST 2.0 extensively on the BiPV-WHF installation, the following recommendations are made with regards to up-grading the user-friendliness and capabilities of PVSYST 2.0:

- Although the 3-D geometric representation input as a highly advanced feature of PVSYST 2.0 as compared to others, it can be improved much more if a commercial CAD software is linked to PVSYST 2.0. For instance PVSYST 2.0 can be made to read and link up with a commercial CAD software.

- The model does not incorporate any building thermal engines that can be used in conjunction with its PV calculator, as witnessed from the significant disparities when predicting the array temperature, and consequently, the hourly DC outputs and thus the global AC output when the PV arrays are integrated on rooftops. This means that the thermal gains from the building itself will inevitably increase the array temperatures, as they form part of the roof. Thus a separate building thermal computer model is suggested to predict the temperatures of the PV arrays in a prospective site and building specific BiPV installation.

For this rest of this research project, the thermal engine simulator, SUNREL 1.0β was used in conjunction with PVSYST 2.0 to enhance the array temperature calculations.

7.6 SUNREL 1.0β

As presented and discussed in the previous section, a thermal simulation engine was needed to enhance the use of the selected BiPV computer model chosen for this research project. A less stringent criteria of selection was applied for the thermal models as compared to the BiPV model. In this case a quick search was made and a user-friendly dynamic thermal computer model, SUNREL 1.0β was chosen. SUNREL 1.0β was a Windows PC-based model that was originally developed as SERIRES by NREL, USA (SUNREL manual, 1997).

7.6.1 Execution of SUNREL 1.0β

This part presents the simulation set-up for the execution of SUNREL 1.0β. It is a relatively straight forward Windows-based, dynamic thermal model. The only external input required by this model is the hourly data for solar irradiance, temperature and windspeed for a complete year.

The structure of the thermal computer model SUNREL 1.0β can be summarised as shown in Figure 7.12:

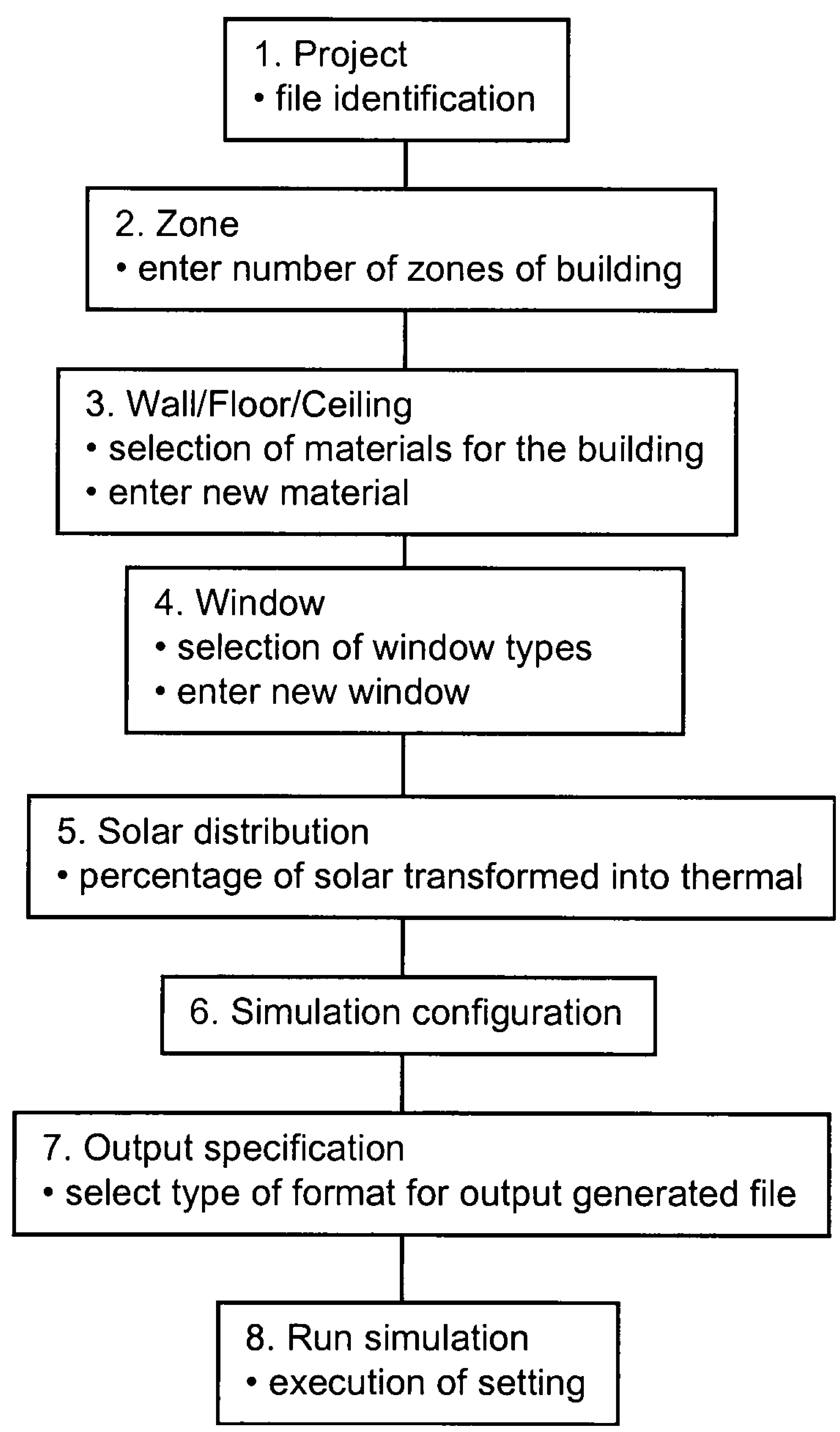


Figure 7.12: Structure of SUNREL 1.0β

A brief account of the items shown in Figure 7.12 is as follows:

1. Project

This is the identification name of the particular building simulation.

2. Zone

The simulation process begins by defining the basic wall, floor and ceiling for any enclosure. Each enclosure is called “Zone”. Thus a simple house that has a living room, a bedroom, a kitchen and a toilet has four zones. Each zone is excluded from the other by walls. The user is then prompted for the basic dimensions, thermal variations (e.g. sensible or latent heat) and the ventilation rates of each zone.

3. Wall/Floor/Ceiling

This menu gives the user a choice of built-in materials for the wall, floor and ceiling. The user can also input new materials that are of known thermophysical properties. The number of nodes is set in this menu. Naturally the higher the number of nodes used, the longer the time it takes to execute the simulation. In this menu, the user also has the option of assigning dimensions and materials for the overhangs and sidefins.

4. Windows

This menu prompts the user to make a selection of the window and types of transparent insulation used. New window materials can also be added, similar to the preceding menu.

5. Solar distribution

This part of the software prompts the user to assign percentages of the solar contribution that is anticipated to be transformed into thermal energy. For instance, the user is prompted to assign the percentage of the solar radiation that is expected to fall on a certain wall and absorbed by it.

6. Simulation configuration

This menu allows the user to assign the met weather station or data and the time period for the simulation.

7. Output specification

This part prompts the user to set the preferred output format to be generated by the model during simulation. It offers simulated output results as monthly, daily or hourly values with all or selected parameters, available in metric or British units.

8. Run simulation

This is the menu that actually starts off the simulation. Any error messages are automatically prompted on the screen.

7.6.2 Limitations of SUNREL 1.0β

Since the software is a beta release, the limitations have been considerable. Amongst them are:

- It does not have any geometrical representation of the buildings set-up. Thus, using it requires a lot of imagination and a good memory track to construct a 3-D geometric dimensions of the building.
- There are several calculations and menus offered but are not in operation yet. Fortunately, the air temperature predictions required for the purpose of this research project was adequate.
- It does not have a user support group at the time of use.

Chapter 8. BiPV-Malaysia: Simulation Set-up and Preliminary Findings

8.1 Introduction

This chapter presents the setting-up process for the BiPV simulation work for the Malaysian applications. The simulation set-up comprised of two parts: a) PVSYST 2.0 simulation and b) SUNREL 1.0β simulation. Prerequisites of the set-ups such as the Malaysian weather data and the Standard Malaysian School Building (SMSB) design are presented. Preliminary executions of the set-ups are discussed and results are analysed to guide later simulations for the final stage. A range of alternative PV array arrangements within the architectural design limits for the average school were studied, leading to the use of the BiPV-SMSB unit bay module as a preliminary simulation set-up. Similar considerations for the thermal simulation using SUNREL 1.0β to enhance the simulation executions in PVSYST 2.0 are presented. As a synergistic beneficial consequence of the thermal simulations using SUNREL 1.0β, the classroom air temperatures were simulated and analyses of the results are presented.

8.2 Meteorological data input

The Malaysian meteorological data (met) data was obtained from two sources, namely:

1. The Malaysian Meteorological Office, Petaling Jaya, Malaysia.
2. The International Solar Irradiation Database (ISID) version 1.0 from the University of Massachusetts Lowell Photovoltaic Program.

The data obtained from the met office in Malaysia consisted of the global horizontal irradiation (GlobHor), sunshine duration hours (SDH), dry bulb ambient temperature (DBT), wet bulb ambient temperature (WBT), relative humidity (RH), wind speed (WS) and wind direction (WD), for the year

1995, all in ASCII format. Only data with regards to solar, temperature and wind speed measurements were extracted. It was also decided at this stage that an alternative source for a longer period of Malaysian irradiation met data be found to serve as a check. This was obtained from the ISID database. The ISID database gave the site location and monthly daily global horizontal irradiation in units of $kWhm^{-2}d^{-1}$ over a period of fifteen years for the Malaysian case. The data was provided in ASCII format with column headings describing the values. These data had been cleansed and were highly reliable since they are statistical compilations over a large number of years. Details of the Malaysian met data have been presented and discussed in an earlier Chapter. The values of solar irradiation from both sources did not differ significantly. In addition, only the met data obtained from the Malaysian met office contained enough information for the purposes of this research. Thus, the Malaysian met data for 1995 were used for the simulations in this research project.

8.3 The Standard Malaysian School Building

The school building, like any other building in Malaysia has to conform to the Malaysian Standard. This standard has been up-graded into by-laws and details of these building by-laws are available in commercial publications (Uniform Building By-Laws, 1996). The relevant section in the by-law that covers school building designs in terms of sustainable energy sources are however, quite minimal and general. An extract of the relevant documents are shown in Table 8.1:

By law no	*Natural lighting and ventilation*
39-3	*Every room used for the purpose of conducting classes in a school shall be provided with natural lighting and ventilation by means of one or more windows having a total area of not less than 20% of clear floor area of such rooms and shall have openings capable of allowing a free uninterrupted passage of air of not less than 10% of such floor area*
	Height of rooms in schools
44-4	*In schools, the height of rooms used for the dissemination of knowledge shall not be less than 3 m headroom*

Table 8.1: Malaysian Uniform Building By-Laws regarding sustainable energy sources.

The Standard Malaysian School Building (SMSB) was designed by the office of The Public Works Department (PWD), Ministry of Works in the Malaysian civil service. The PWD have compiled past experiences and have produced two standard designs for the SMSB, namely: a) architectural design and b) mechanical and electrical (M&E) design. Both of these designs have been instituted so as to meet the needs of the typical standard Malaysian school size. Most of the architectural SMSB design in the by-law deals with structural strengths and safety aspects. The standard M&E drawings depict the typical electrical equipment for the SMSB design (Technical Guidelines Electric Branch, 1985).

8.3.1 Architectural design

The SMSB design is based on a unit bay module that is duplicated according to the size of the schools. The basic bay module is then duplicated to form blocks of buildings with specific purposes such as classrooms, administration offices, teachers rooms, activities rooms and specialised rooms. Details of the standard architectural plan for the SMSB are available from the Public Works Department, Ministry of Work, Malaysia (Standard School, 1991). A presentation of the architectural design of the SMSB is best accompanied with photographs and diagrams as shown in the following sections.

Photograph 8.1: Perspective view of a Standard Malaysian School Building.

Photograph 8.2: Side view of an SMSB design.

Photograph 8.3: Awning of the SMSB design.

The schematic diagrams of the SMSB design are shown in the following figures:

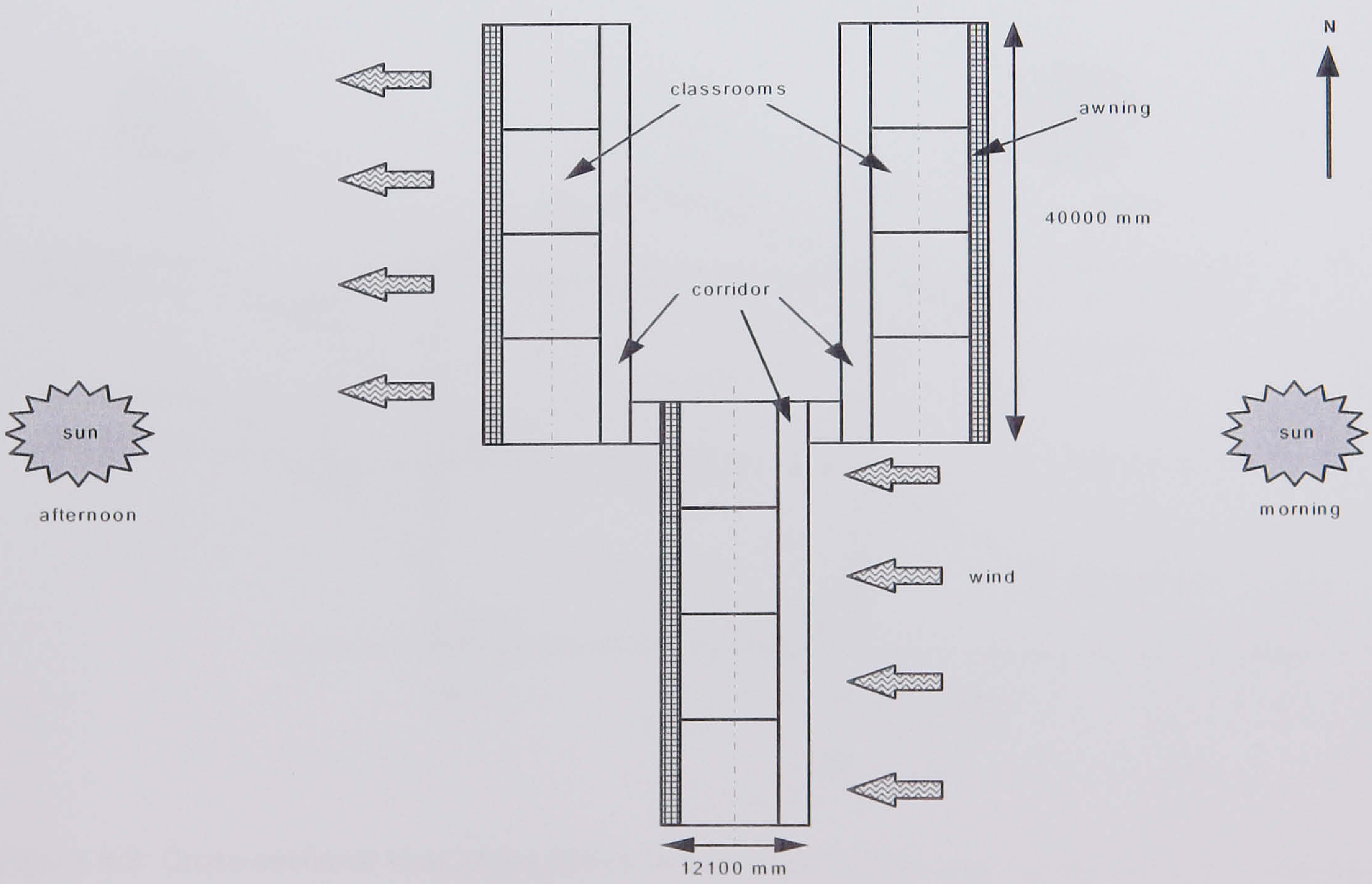


Figure 8.1: Layout of the SMSB classroom blocks with a North-South longitudinal axis preference.

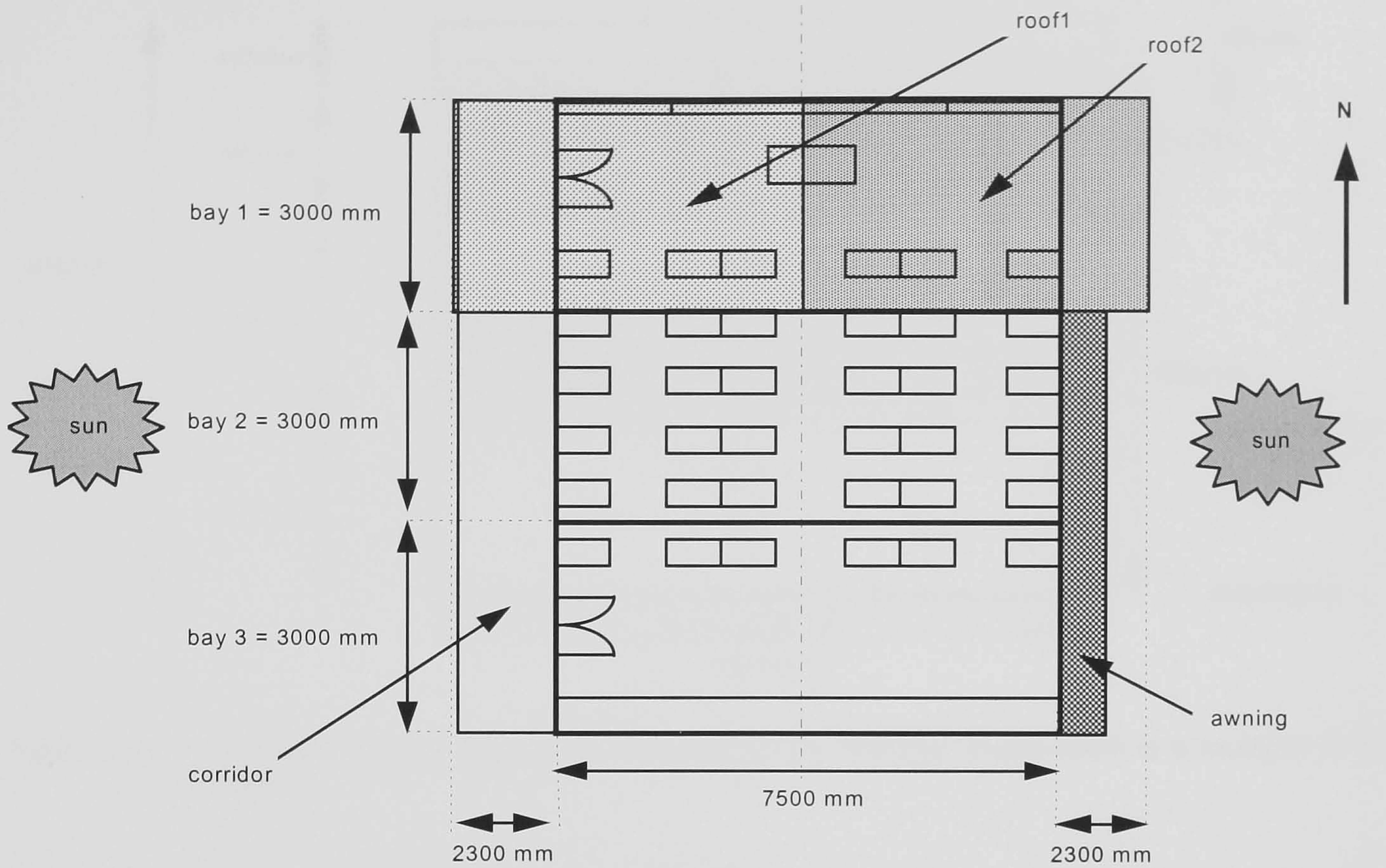


Figure: 8.2: Plan view of the SMSB design showing a single classroom. The basic SMSB classroom is made up of three basic modules. The total PV integrable surface area of the awning per bay module is 3.6 m^2 and for a single roof is 19.7 m^2.

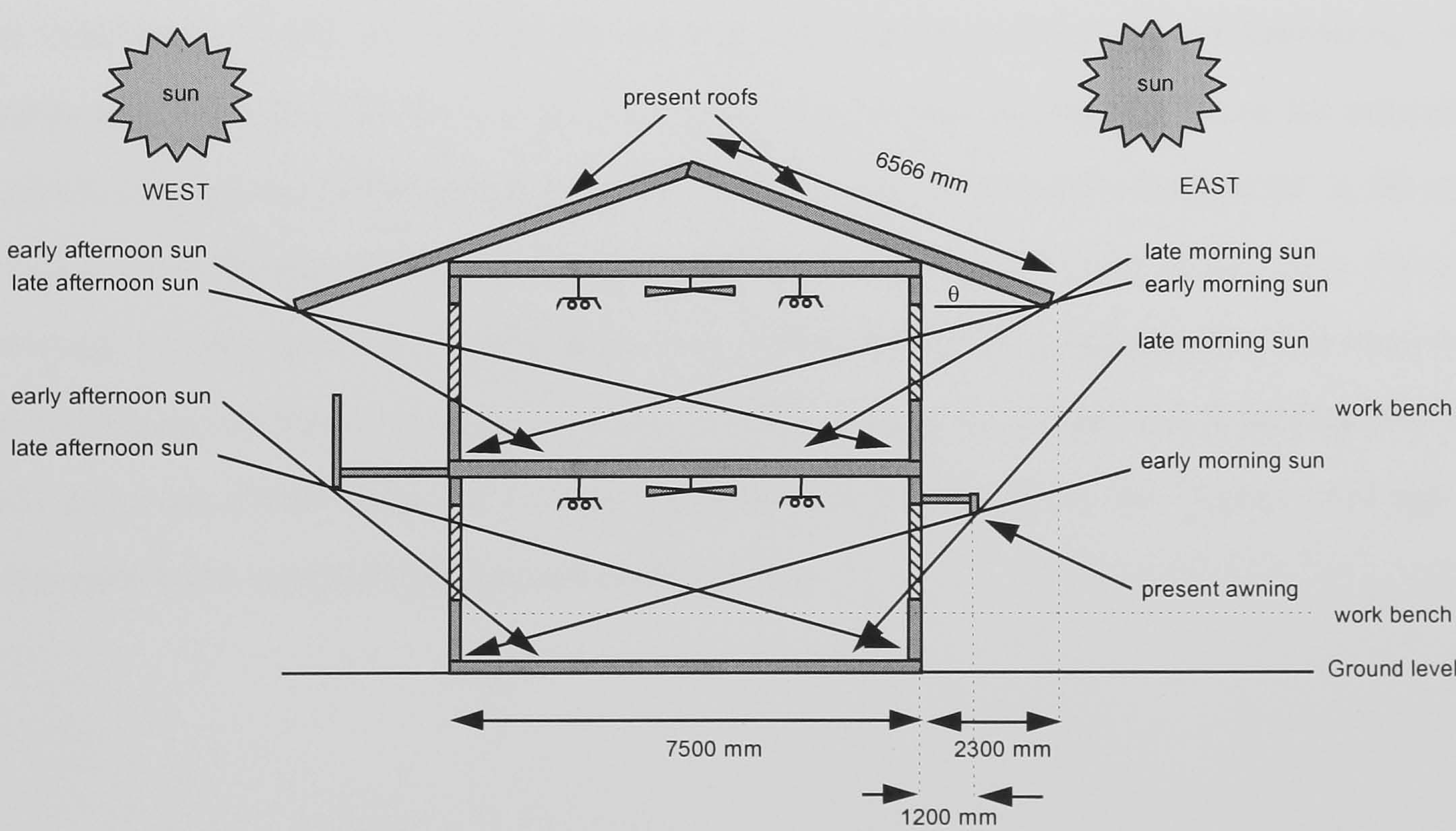


Figure 8.3: Cross-sectional view of the SMSB design showing the depth of the sun's rays that has been designed to meet the Malaysian by-laws for shading and daylighting.

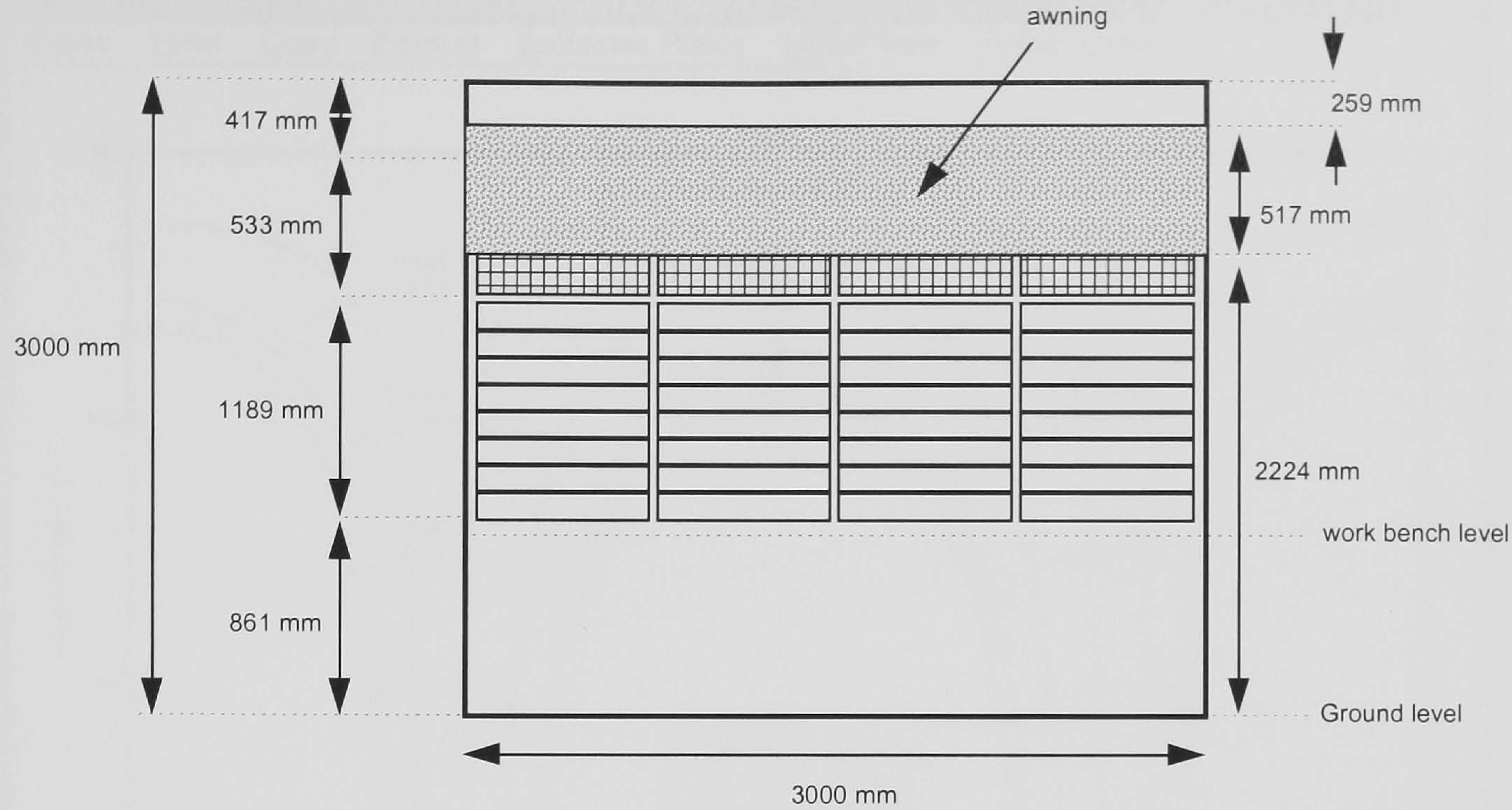


Figure 8.4: Front view of an SMSB design showing a bay module. Every room is a multiple of this bay module.

From Figure 8.1, it can be seen that the preferred plan layout of the SMSB design is along the North-South longitudinal axis. This is so that the awning side faces the rising sun when the ambient temperature is still relatively low as the school session starts at 0730 hours in the morning and ends at 1330 hours. As the sun reaches mid-morning, the extended awning and the East-facing roof would play their roles. The often direct evening sun rays are then partially blocked by the extended corridor and roof on the West-facing side. Due to the latitude of the country at about 04^0 N, the sun hovers above the head during most of the day. Based on the azimuth charts of sun-paths, the sun is mostly situated above the head for most of the period during the school session. This has been anticipated earlier thereby explaining the rationale for proposing the PV modules to be integrated on the roof of the SMSB design as much as possible, as is proven later in this Chapter. This fact is illustrated by the sunpath chart as shown in Figure 8.5:

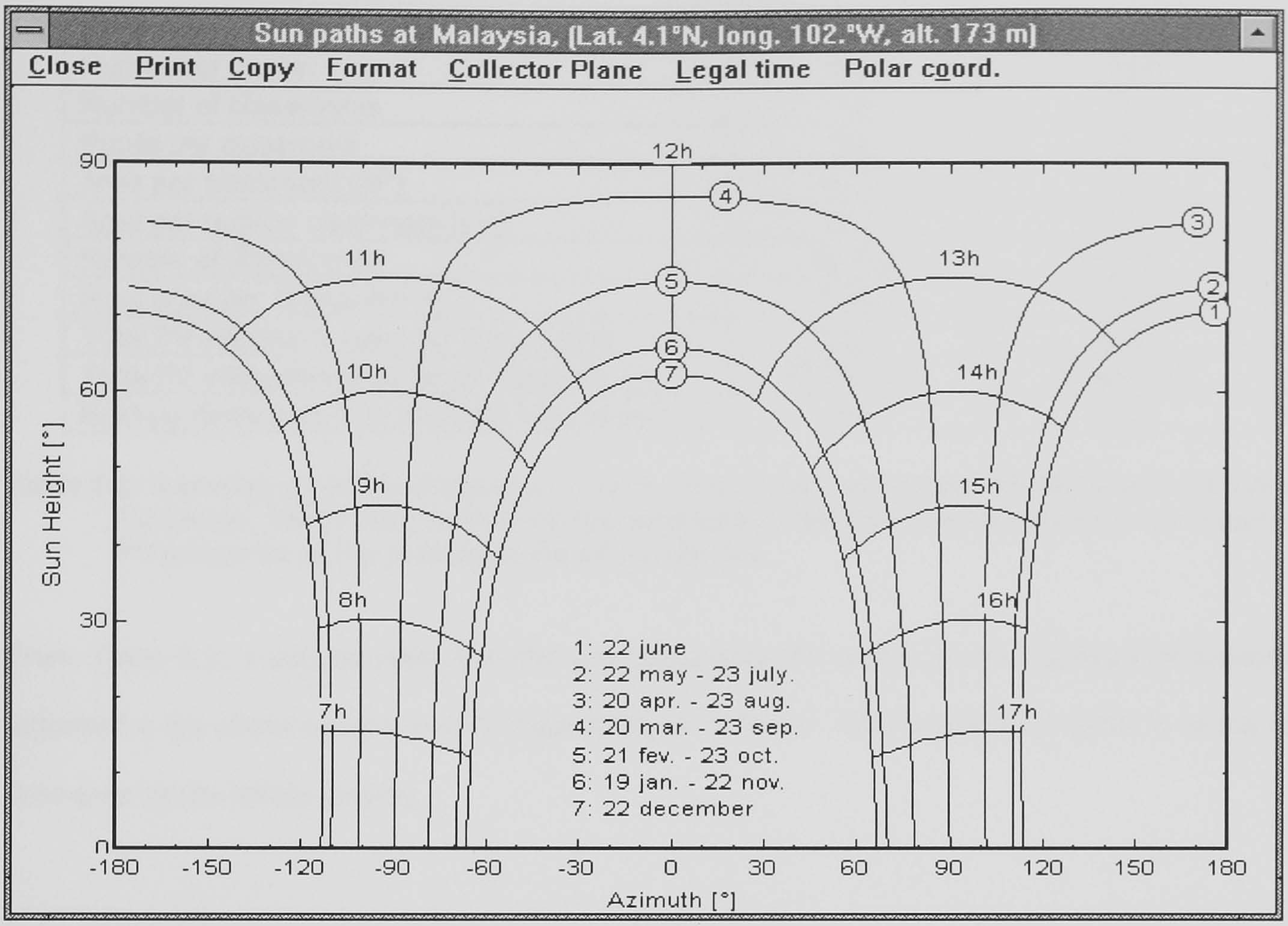


Figure 8.5: Sunpath chart for Malaysia. It shows that the sun rises high daily throughout the whole year. This explains the reason for integrating the PV arrays onto the roofs.

8.3.2 School size

The SMSB design caters for all the types of government-owned and maintained public schools in Malaysia. There are two main divisions of schools, i.e. the primary and secondary schools. The major architectural difference between the two is the number of levels for each type. This comes about due to the size of the two divisions of schools and the academic activities planned for the primary and secondary schools. The average sizes of the SMSB design for the primary and secondary schools are summarised in Table 8.2:

Parameter	Primary SMSB	Secondary SMSB
Number of pupils	405	1167
Number of classrooms	12	33
Pupils per classroom	33	35
Area per classroom (m^2)	67.5	67.5
Area per pupil in classroom (m^2)	2.1	1.9
Number of classrooms	86,569	50,661
Roof area per classroom (m^2)	118.2	118.2
Total PV integrable area per school (m^2)	1,418	3,901
Total PV integrable area for all Malaysia (m^2)	10,232,456	5,988,130
Built-up classroom floor area per school (m^2)	808	2,223

Table 8.2: Summary statistics of average sizes for primary and secondary SMSB design (Ministry of Education, 1997). Also shown are the estimates of the total area of possible roof-integrable PV arrays for all the schools in the whole country.

From Table 8.2, it can be seen that the total integrable PV arrays on the rooftops of Malaysian schools for the whole country is very large at about 16.2 km^2. This is less than 0.005 % of the total land area for the whole country.

8.3.3 Mechanical and electrical design

This design has only one standard and comes in after the architectural design has been approved. It basically contains the standard Mechanical and Electrical (M&E) drawings for the adequate supply of power demand for the school. The drawings contain standard circuit and wiring diagrams for each classroom, block and special needs of the school, depending on its division and types of use. Details of the standard M&E wiring diagrams are available from the Public Works Department, Ministry of Works Malaysia (Technical Guide Electric Branch, 1985). The typical SMSB M&E wiring diagram is shown in Figure 8.6:

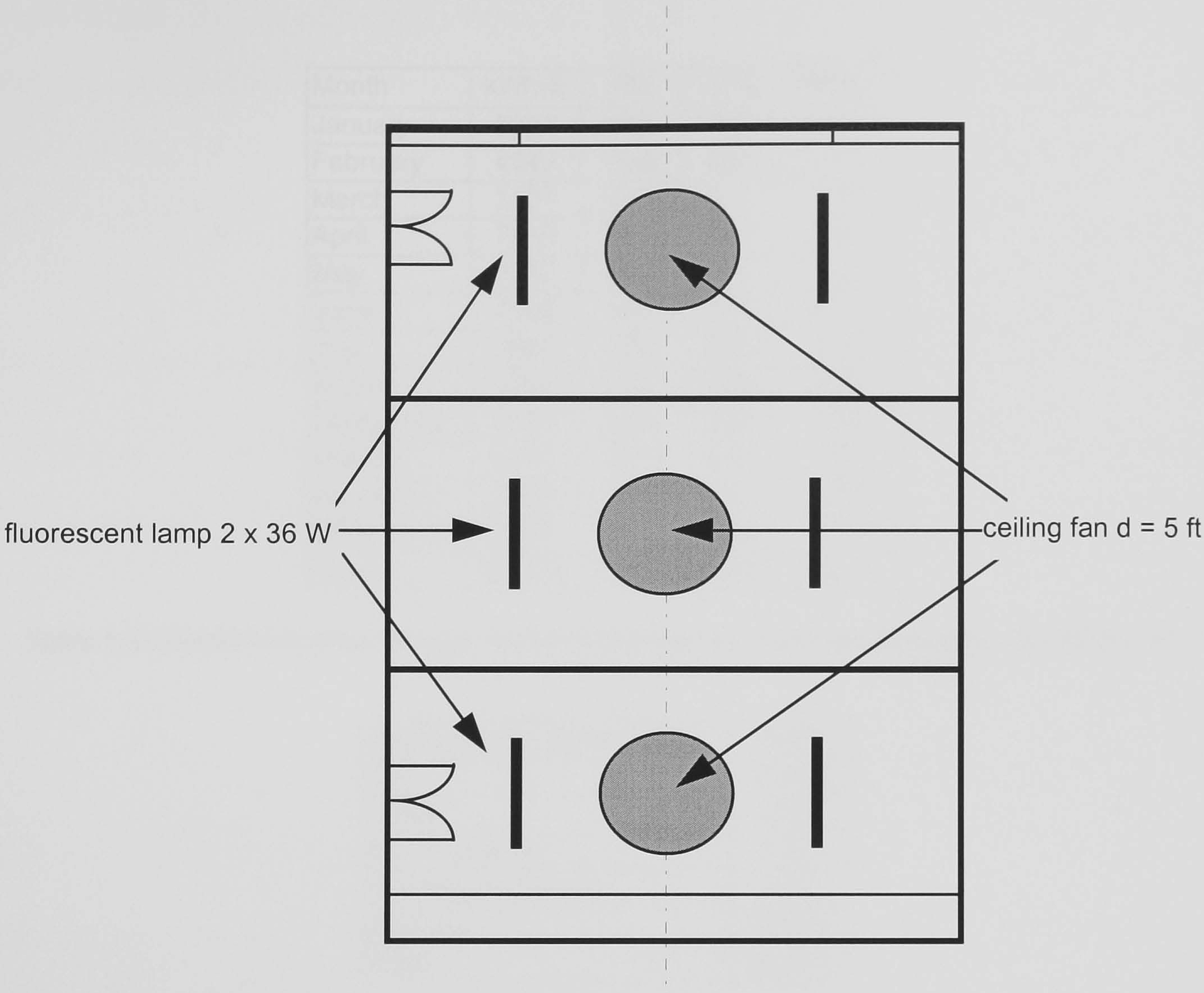


Figure 8.6: Typical SMSB M&E wiring diagram per classroom. d - diameter.

The energy requirement of the SMSB school is best presented as per classroom need. This is the conventional practice since the M&E design has always been based on the classroom. A typical SMSB classroom would be equipped with the following common electrical equipment:

Equipment	Rating	Model
• Lighting	2 x 36 W	Fluorescent fitting
• Ceiling fan	40 W	1524 mm diameter sweep
• Power point	1450 W	3 pin

Based on sample data, the electrical energy requirement of the SMSB school can be summarised as shown in Tables 8.3 and 8.4:

Month	kWh-E	RM	US$	$kWhm^{-2}$
January	5854	1405	526	2.28
February	4549	1092	409	1.77
March	7101	1704	638	2.77
April	7010	1682	630	2.73
May	7782	1868	700	3.03
June	7505	1801	675	2.92
July	9860	2367	886	3.84
August	10842	2602	975	4.22
September	8706	2089	783	3.39
October	9237	2217	830	3.60
November	9237	2217	830	3.60
December	2887	693	259	1.12
Total	90570	21737	8141	40.74

Table 8.3: Monthly electrical energy requirement taken for a sample secondary SMSB school.

Yearly energy consumption	kWh
Fan	27888
Lamp	51581
Air conditioner	4050
Auxiliary equipment	7051
Gas use	10644
Total	101213

Table 8.4: Total energy consumption for an SMSB p.a.

Based on data from Table 8.2 and Table 8.4, the statistics for a secondary SMSB school show that it has 33 classrooms with an energy consumption of 90570 kWh p.a. Thus the electrical energy requirement by the SMSB school per classroom is theoretically about 2,745 kWh p.a. Thus the BiPV generation will be basically targeted to meet this demand as much as possible.

8.4 Simulation set-up

8.4.1 PVSYST 2.0

The setting-up for the preliminary execution of the computer model PVSYST 2.0 for the Malaysian BiPV simulations required similar procedures as explained in an earlier chapter for the BiPV-WHF simulations. The procedure was repeated here with a few adjustments, namely, the met data, the 3-

D geometrical near shading configurations and the BiPV wiring connections. All SMSB designs were based on the bay module as shown and discussed earlier. The placement of the BiPV arrays as part of the roof and awning devices of the SMSB classroom design were explored in these preliminary executions.

8.4.1.1 Meteorological data set-up

The monthly met data for the global solar irradiation on the horizontal, ambient temperature and wind speed were fed into the computer model PVSYST 2.0. In the first round of executions, simulations were run based on these monthly parameters. In the second round, the met data were input as hourly values within the computer model, and then the execution runs were made to produce standard results.

8.4.1.2 Architectural set-up

For the pilot execution, the architectural set-up was made in such a way that the PV modules covered as much of the SMSB bay module awning and roofing as possible. This gave an indication as to the maximum BiPV integration possible in the SMSB design. The architectural design of the SMSB is such that the awning always points in the same general direction as one of the roofs, while the other roof would always faces the opposite general direction. Thus the longitudinal axes of the simulations were aligned for the North-South axis and the East-West axis in th computer model set-up. Consequently, the orientation set-up of the BiPV arrays came in three sub-arrays, namely; sub-array 1, sub-array 2 and sub-array 3. Sub-array 1 consisted of PV modules for the awning, sub-array 2 consisted of PV modules for roof 1 and sub-array 3 consisted of PV modules for roof 2. Each combination of North-facing, South-facing, East-facing and West-facing BiPV sub-arrays from the roofs and awnings were then simulated separately. Detailed drawings of each BiPV sub-array were input into the 3-D geometrical algorithm of PVSYST 2.0 with the correct dimensions. The orientation combinations of the three BiPV sub-arrays are summarised in Table 8.5:

	Sub-array 1 - awning	Sub-array 2 - roof 1	Sub-array 3 - roof 2
First run	N	N	N
Second run	S	S	S
Third run	E	E	E
Fourth run	W	W	W

Table 8.5: BiPV combination of orientations for preliminary execution of simulation. N - North-facing; S - South-facing; E - East-facing; W - West-facing. See also Figure 8.7

The combinations described above are best illustrated in Figure 8.7:

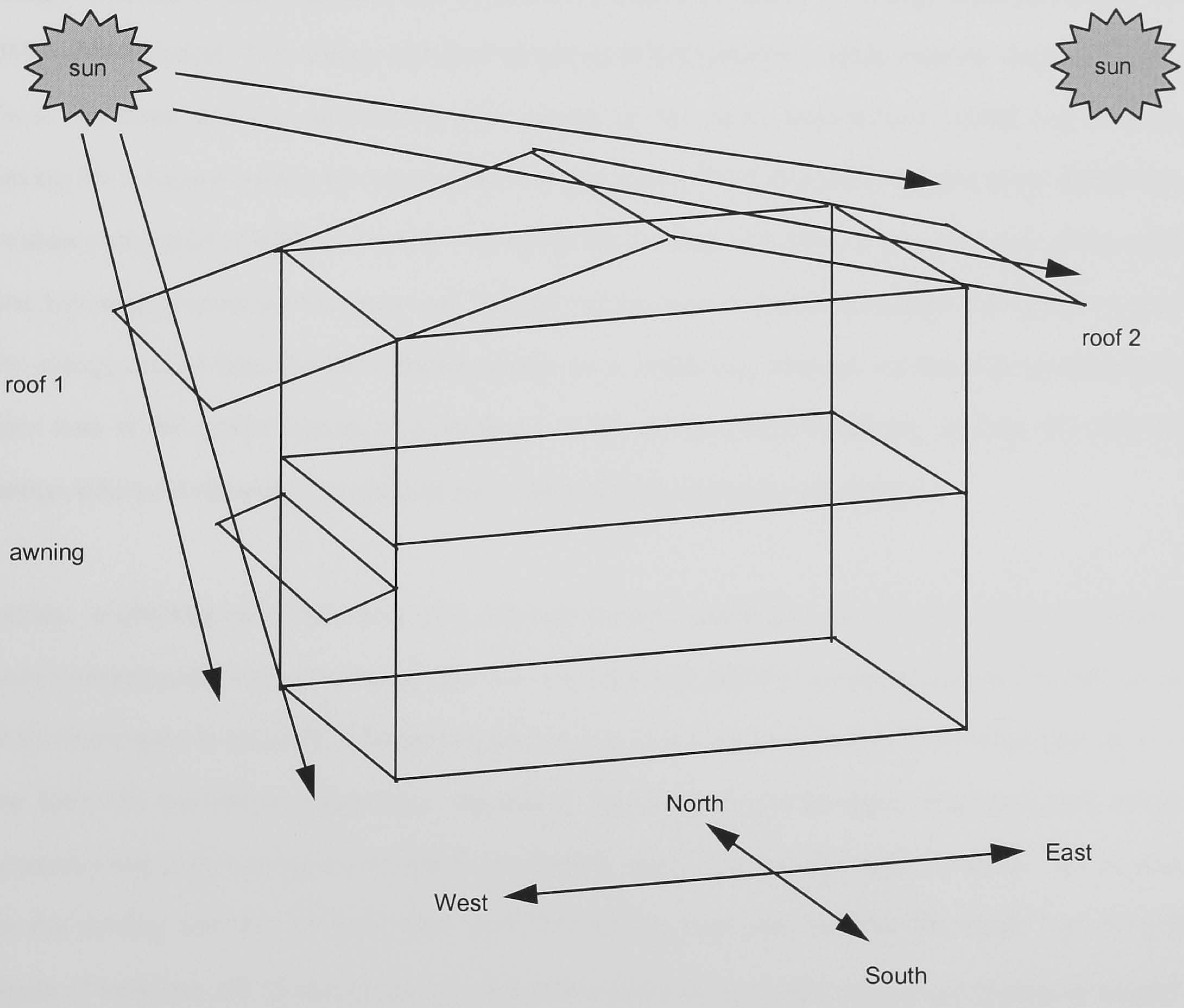


Figure 8.7: PVSYST 2.0 set-up in 3-D geometrical representation of SMSB bay module with PV arrays integrated on the awning and both sides of the roofs.

These configurations were retained for each simulation execution and results for the shading factors and geometrical representations were then produced.

8.4.1.3 BiPV system set-up

The final wiring connections of the PV array would have to meet expectations with regards to the required energy demand, the solar input, architectural and scientific constraints, economics, safety of handling a combination of DC voltages, AC outputs, and for operations and maintenance works. However, since this was an initial stage of the BiPV-SMSB simulation, it was decided that the criteria selected would be based on maximising the PV integrable surface areas of the SMSB design. This would give a general idea as to the maximum PV power theoretically achievable for the BiPV-SMSB design. The design included simplicity of connections, safety aspects and aesthetics. Thus this initial stage of simulations were based on the basic architectural SMSB bay module, having PV arrays covering the awning and the two roofs. Thus one basic architectural SMSB bay module comprised of BiPV sub-array 1 covering the awning, sub-array 2 covering one of the roofs and sub-array 3 covering the other roof. The sum of the output of each sub-array then gave the total PV energy output from the BiPV-SMSB design as a whole bay module. As the built-up classroom floor area of the school increased in multiples of the architectural SMSB bay module, the total PV design was consequently a multiple of each BiPV-SMSB classroom generation.

Initially, a plethora of components and different wiring connections of the PV string combination were contemplated. It was finally decided that the Siemens M55 PV modules and the PV-WR series of inverters were to be used in these simulations due to the experience and confidence gained from the BiPV-UK foundation experience. Moreover, the cost of the Siemens M55 per peak power produced has been among the lowest in the market within this popular range of sizes. The inverter for the awning was the PV-WR 1500 while that for the roof was the PV-WR 1800. The PV-WR series of inverters are produced by an established manufacturer that have been producing smaller versions of a family of inverters that are even more user-friendly. Thus inverters from this manufacturer were chosen for the simulation work in this project. Details of these components are shown in Table 8.6:

Parameters	PV module	Inverter 1	Inverter 2
Nominal output power (W DC)	55 W DC	1500 W AC	1800 W AC
Module area (m^2)	0.43	-	-
Reference temperature (^oC)	25	-	-
Temperature coeff. for current (mA^oC^{-1})	2.3	-	-
Temperature coeff. for voltage (mV^oC^{-1})	-73	-	-
Current at maximum power (A DC)	3.1	-	-
Voltage at maximum power (V DC)	17.4	-	-
Efficiency during operation (%)	12.5	90	90
Nominal output voltage (V AC)	-	230	230
Minimum operation voltage (V DC)	-	80	80
Maximum operation voltage (V DC)	-	130	130

Table 8.6: Details of the PV module and inverter used in the SMSB simulation.

Thus with these aspects in mind, the awning (sub-array 1) consisted of a single string of six PV modules connected in series, and each of the roofs (sub-arrays 1 and 2) consisted of six parallel strings of six PV modules connected in series per string. The wiring connections set-up of the BiPV-SMSB bay module are shown in Figure 8.8:

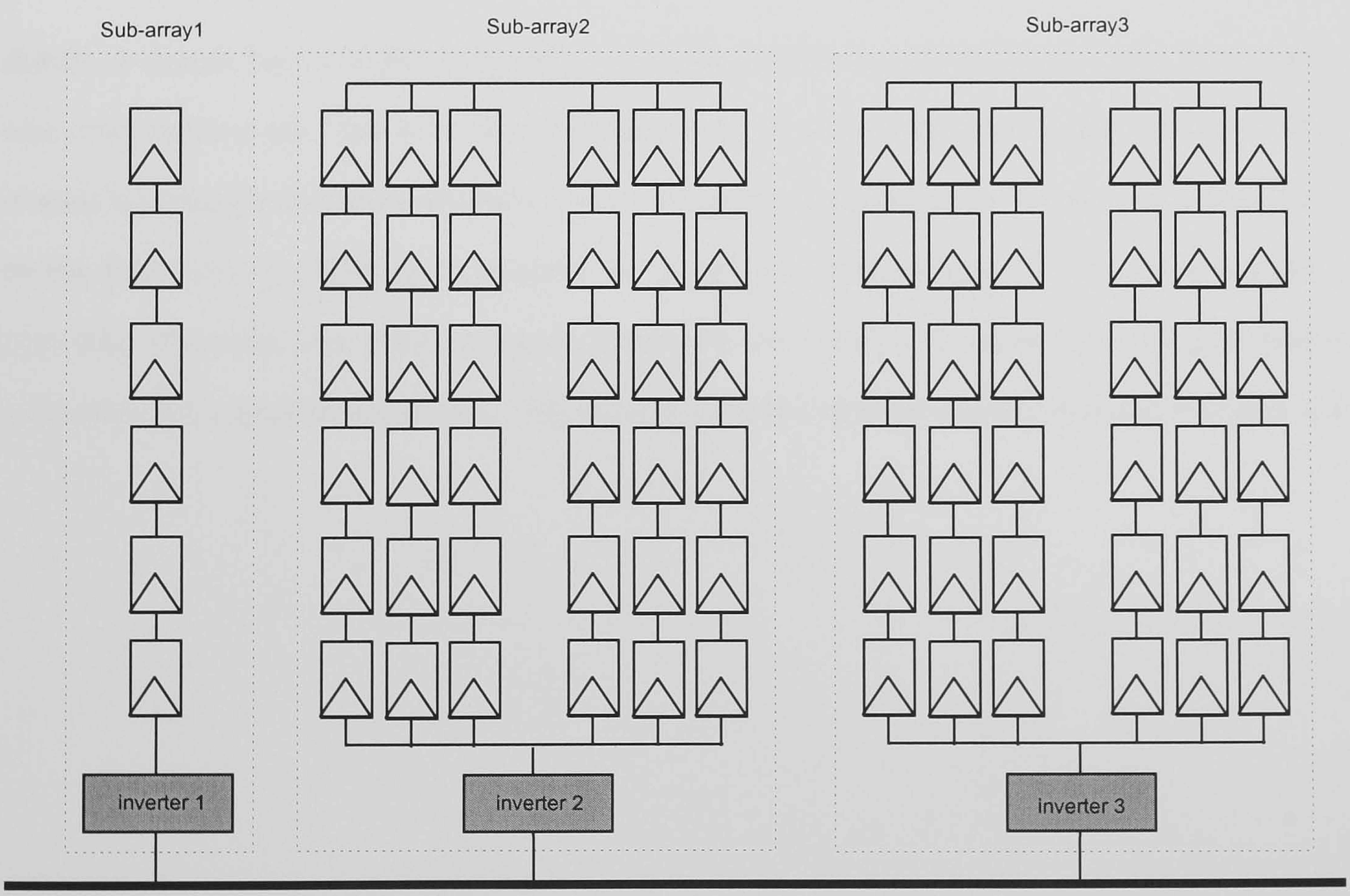


Figure 8.8: Wiring connections of BiPV system for SMSB bay module simulation. This combination uses the maximum integrable PV area of the SMSB design.

This BiPV-SMSB bay module wiring arrangement gave a nominal output voltage of 104.4 V DC and a current of 3.1 A DC and a maximum power of about 0.3 kWp DC from the awning. Since the wiring arrangements for the two roofs were similar, each then gave a nominal output voltage of 104.4 V DC and a current of 18.3 A DC and a maximum power of about 1.9 kWp DC. As the BiPV-SMSB sub-arrays 1, 2 and 3 were all connected in parallel, the total PV output voltage was then 104.4 V DC, the current was 21.4 A DC and the power was 2.2 kWp DC per SMSB bay module. The PV arrays covered a maximum allowable area of about 72 % of the total awning area and about 79 % of the total area of each roof. With these settings, the pilot execution of the BiPV-SMSB simulations was commenced.

8.4.2 Preliminary findings

8.4.2.1 BiPV as awning device

Based on results from the pilot executions, it was found that the performance of the BiPV-awning was unacceptably low. This is a natural consequence of its architectural location, which is being shaded significantly during the operating hours. Moreover, since the BiPV-awning was placed either on the East-facing or West-facing facades, its surface was obstructed about half the time within a solar day. This would give grave consequences to the life of the PV modules themselves as well as a questionable economic investment. The shading chart for the BiPV-awning is shown in Figure 8.9:

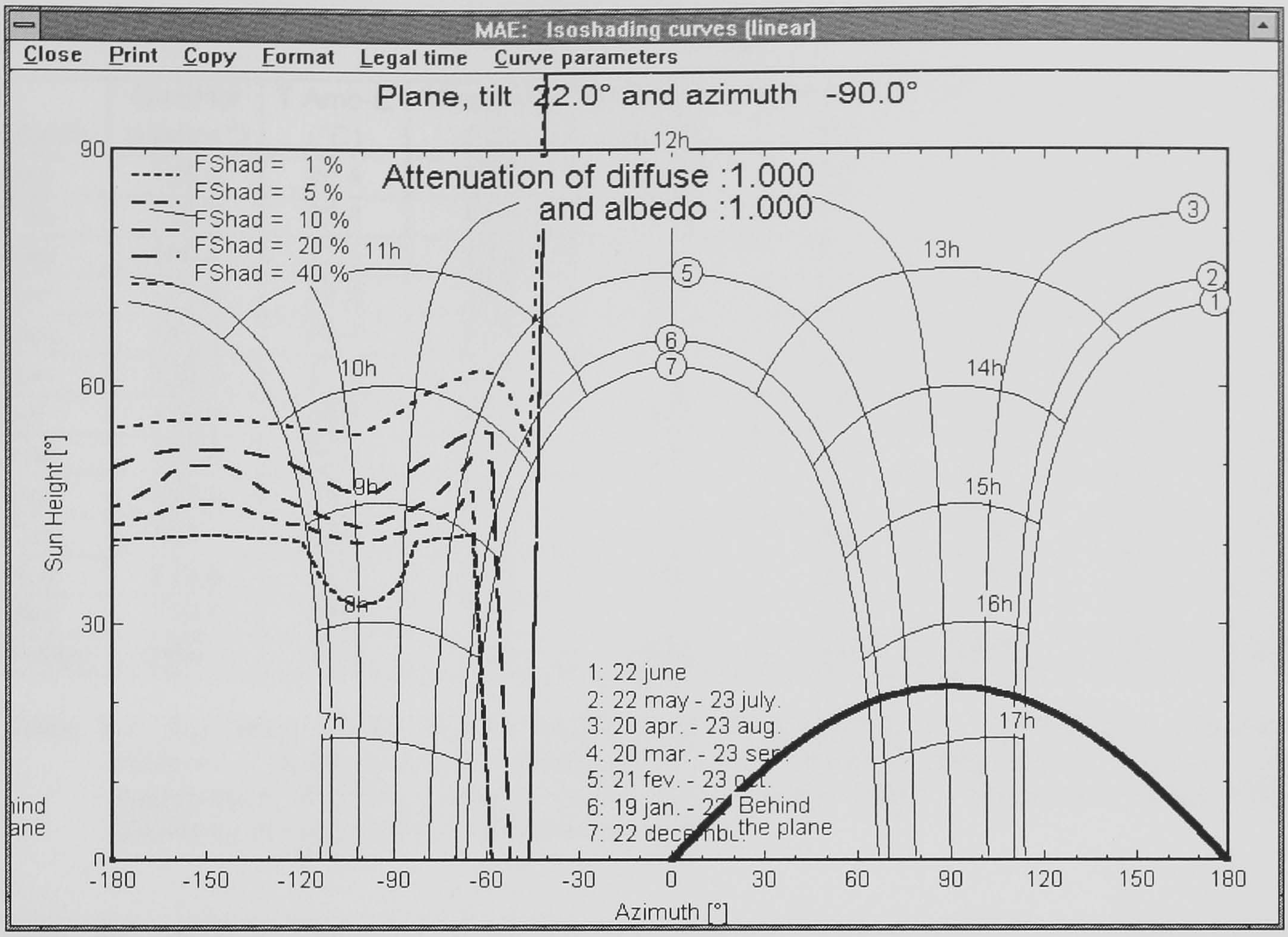


Figure 8.9: Shading chart of the BiPV-awning for the SMSB East-facing bay module. The PV array as awning device are shaded about more than half of the daytime and is shown by the area under the dotted lines.

From figure 8.9, it can be seen that the PV modules on the awning suffer gravely from shading casted by the East-facing roof. The same is true for the West-facing, North-facing and South-facing awnings. This has been anticipated due to the architectural design of the SMSB. As an example, details of the simulated preliminary results for the East-facing roof are shown in Table 8.7:

Month	GlobHor ($kWhm^{-2}$)	T Amb-E (°C)	TArray-AE (°C)	EOutInvA-E (kWh)	EffArrA-E (%)	EffSyA-E (%)	EffInvA-E (%)	PRA-E (%)
Jan	158.4	26.4	38.8	8.6	3.7	2.1	57.7	18.5
Feb	156.0	26.8	43.1	10.0	4.1	2.5	61.8	22.0
Mar	180.4	27.1	40.2	10.2	3.9	2.3	58.4	19.7
Apr	175.2	27.2	39.1	9.3	3.8	2.1	56.2	18.5
May	165.2	27.4	40.5	9.5	4.0	2.3	56.4	19.7
Jun	153.0	27.3	39.2	8.3	4.0	2.2	54.8	19.2
Jul	158.4	26.9	38.8	9.5	4.2	2.4	56.2	20.5
Aug	157.8	26.9	38.3	8.3	3.8	2.1	54.3	18.0
Sep	153.3	26.7	38.3	7.6	3.6	2.0	54.5	17.2
Oct	154.1	26.6	37.2	7.0	3.5	1.8	51.7	15.9
Nov	133.8	26.3	38.4	6.0	3.4	1.8	53.1	15.6
Dec	136.4	26.3	37.7	5.7	3.2	1.7	51.1	14.3
Tot/av	1882.0	26.8	39.1	99.8	3.8	2.1	55.8	18.4

Table 8.7: Simulated results of BiPV-SMSB East-facing awning. A - awning; E - East-facing; GlobHor - global horizontal irradiation; T Amb - ambient temperature; T Array - array temperature; EOutInv - energy output from inverter; EffArr - efficiency of array; EffSy - efficiency of system; PR - Performance Ratio.

From the values in Table 8.7, it can be seen that the BiPV system on the awning suffered tremendously from shading, thereby producing hotspots, which would damage the solar cells. This has been shown from the shading chart in Figure 8.9 earlier. As a consequence, the system gave a very poor performance by having a monthly PR ranging from about 14 to 22 % with an average of only 18.4 % which is not acceptable by normal standards. Thus from here, it becomes apparent that the issue of using the PV modules as a means of controlling the amount of shading and daylighting as awning devices on the building, like the applications in Northern latitude climates, would certainly be an unwise option, technically as well as economically. Furthermore, the issue of daylighting in Malaysian schools has not been a major one as compared to Northern latitude climates such as the UK. This has also been observed from first-hand experience as well as from the global solar irradiation records in Malaysia which averages about 5 $kWhm^{-2}d^{-1}$. Instead, a more relevant issue experienced first-hand was related to the air temperatures inside such buildings, both in the attic space as well as the habitated classrooms. Based on these results, it was decided that the only acceptable option for BiPV-SMSB applications would be on the roof, as was mentioned earlier.

8.4.2.2 *BiPV as roofing material*

The performance of the BiPV-roof was as anticipated, giving PR values in excess of 60 % for all the main orientations. These generations are on the higher side, after taking into consideration the fact that both pairs of the North and South facings roof, as well as the East and West facing roofs have directions facing away from each other. This means that each of the BiPV roof pairs are obstructed from direct solar radiation during some portions of the day. As an example, the simulated results for the BiPV pilot East-facing and West-facing roofs are shown in Tables 8.8 and 8.9:

Month	GlobHor ($kWhm^{-2}$)	T Amb-E (°C)	TArrayR-E (°C)	EOutInvR-E (kWh)	EffArrR-E (%)	EffSyR-E (%)	EffInvR-E (%)	PRR-E (%)
Jan	158.4	26.4	46.9	195.1	9.3	8.2	87.9	66.3
Feb	156.0	26.8	48.1	169.8	8.3	7.3	87.8	59.1
Mar	180.4	27.1	47.8	204.9	8.8	7.7	87.9	62.4
Apr	175.2	27.2	47.8	211.8	9.4	8.2	87.9	66.7
May	165.2	27.4	46.9	203.8	9.4	8.3	87.8	67.2
Jun	153.0	27.3	45.9	191.8	9.8	8.6	87.8	69.7
Jul	158.4	26.9	45.6	205.9	9.9	8.7	87.9	70.2
Aug	157.8	26.9	45.5	198.7	9.7	8.5	87.7	68.6
Sep	153.3	26.7	45.3	188.4	9.5	8.4	87.6	67.6
Oct	154.1	26.6	44.8	194.9	9.8	8.6	87.8	69.8
Nov	133.8	26.3	43.8	163.9	9.5	8.3	87.4	67.4
Dec	136.4	26.3	44.6	170.3	9.6	8.4	87.6	68.0
Tot/av	1882.0	26.8	46.1	2299.5	9.4	8.3	87.8	66.8

Table 8.8: Simulated results of BiPV-SMSB per bay module for the East-facing roof. R - roof.

Month	GlobHor ($kWhm^{-2}$)	T Amb-E (°C)	TArrayR-E (°C)	EOutInvR-W (kWh)	EffArrR-W (%)	EffSyR-W (%)	EffInvR-W (%)	PR-W (%)
Jan	158.4	26.4	44.0	163.6	8.1	7.1	87.5	57.4
Feb	156.0	26.8	45.9	149.8	7.5	6.5	87.6	53.0
Mar	180.4	27.1	45.4	177.2	7.6	6.7	87.7	54.1
Apr	175.2	27.2	45.5	179.3	7.9	6.9	87.7	56.2
May	165.2	27.4	45.3	183.9	8.7	7.7	87.6	62.1
Jun	153.0	27.3	45.3	187.7	9.4	8.2	87.7	66.7
Jul	158.4	26.9	44.3	189.9	9.4	8.3	87.7	67.0
Aug	157.8	26.9	44.6	188.1	9.3	8.2	87.6	66.1
Sep	153.3	26.7	43.7	168.7	8.5	7.5	87.5	60.4
Oct	154.1	26.6	44.6	195.7	9.7	8.5	87.7	69.1
Nov	133.8	26.3	43.5	162.5	9.3	8.1	87.5	65.9
Dec	136.4	26.3	43.2	158.5	8.9	7.8	87.4	63.3
Tot/av	1882.0	26.8	44.6	2104.7	8.7	7.6	87.6	61.6

Table 8.9: Simulated results of BiPV-SMSB per bay module for the West-facing roof. R - roof

A summary of output results from all other orientation combination is shown in Table 8.10 and Figure 8.10:

Position	Awning			Roof		
	EOutInv (kWh)	EffSy (%)	PR (%)	EOutInv (kWh)	EffSy (%)	PR (%)
First	W - 167.4	W - 3.6	W - 31.0	E - 2299.5	E - 8.3	E - 66.8
Second	E - 99.8	E - 2.1	E - 18.4	N - 2233.0	N - 8.2	N - 66.7
Third	S - 92.9	S - 2.0	S - 17.2	S - 2203.0	S - 7.9	S - 64.2
Fourth	N - 79.9	N - 1.7	N - 15.1	W - 2104.7	W - 7.6	W- 61.6

Table 8.10: Summary of performance results of BiPV-SMSB per bay module from different orientations.

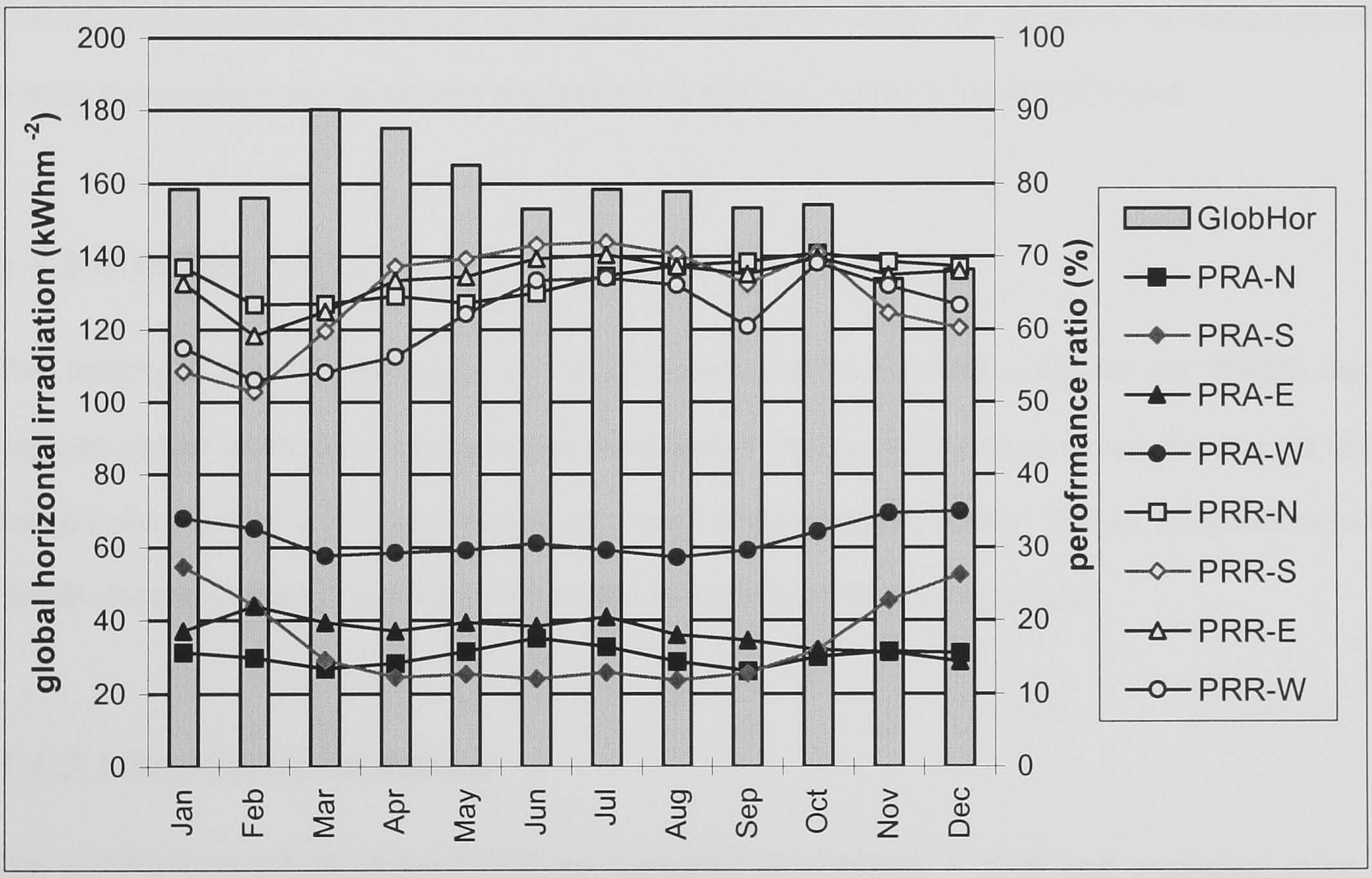


Figure 8.10: Performance of different BiPV-SMSB orientations per bay module. GlobHor - global horizontal irradiation; PR - Performance Ratio; N - North-facing; S - South-facing; E - East-facing; W - West-facing; A - awning; R - roof.

The roof gave much higher outputs than the awning, thus making it the most optimum option of BiPV application in the SMSB design. The results from Tables 8.8, 8.9 and 8.10, show that the PV energy generated from the North-facing, South-facing, East-facing and West-facing roofs do not differ significantly. The outputs are in the range of 2104 to 2233 kWh with a PR ranged from 61.6 to 66.8 %. The N-S and E-W roof pairs give about equal outputs and the difference between having the PV modules placed on the either one of the pairs is negligible. These results are illustrated graphically in Figure 8.10. Since the choice of using the East-West roof orientation would cause the least amount of disruption to the existing design, it was then decided for the rest of this project to have the PV modules integrated on the East-facing and West-facing roofs.

The preliminary set-up using the basic SMSB bay module design produced PV energy roughly up to about 80 % of the required energy demand of 2,745 kWh per SMSB classroom. Considering aesthetic and practical aspects of the integration, the PV modules appear best if they are integrated on the roofs of the SMSB classroom as a basis of design rather than the SMSB bay module design. The set-up and results of the final BiPV-SMSB simulations, which are based on the actual electrical energy requirement per classroom are presented and discussed in the next Chapter.

8.4.3 SUNREL 1.0β

The setting-up for the execution of the computer model SUNREL 1.0β for the SMSB design required similar procedures as explained in an earlier chapter for the thermal simulations. All SMSB designs were based on the bay module as shown and discussed earlier. The air temperature in the SMSB classroom design were then simulated in these preliminary executions.

8.4.3.1 Architectural set-up

The architectural set-up of the SMSB for execution in SUNREL 1.0β is best explained using the sketch shown in Figure 8.11:

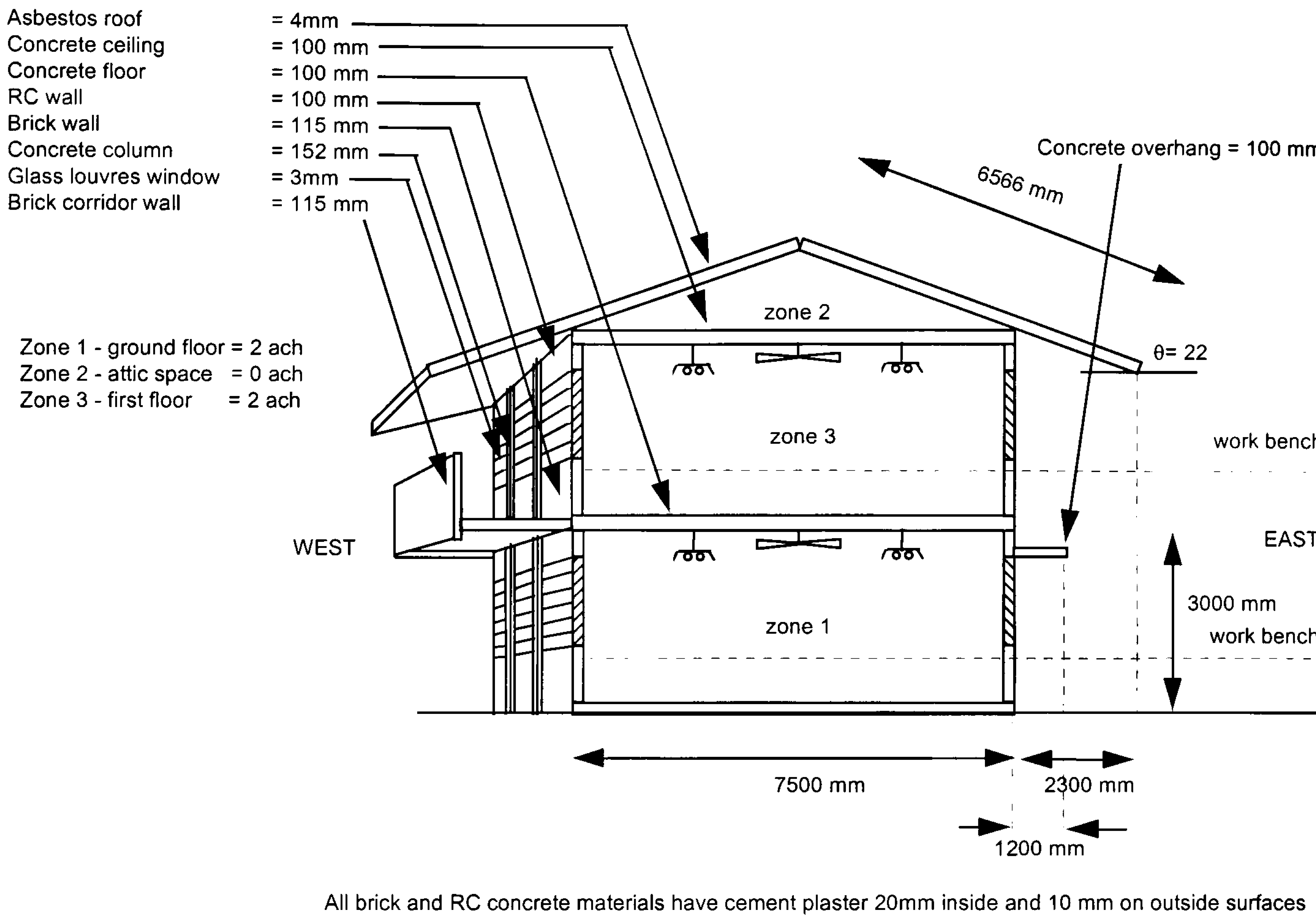


Figure 8.11: SMSB set-up for SUNREL 1.0β showing zone 1, zone 2 and zone 3.

The SMSB classroom was divided into three zones, namely: zone 1 - the ground floor, zone 2 - the attic space, zone 3 - the first floor. All the required information for the successful execution of SUNREL was input into the relevant menu, using standard building material for the SMSB. The building materials for the wall, floor, overhang and corridor were the basic brick and concrete with cement plaster on both sides. The roof and ceiling were made from asbestos sheets. The dimensions of the materials are shown in Table 8.11:

Material	Length	Width	Thickness
Ground floor - concrete	9 m	7.5 m	0.1 m
Brick wall	9 m	1 m	0.115 m
Concrete wall	9 m	0.4 m	0.1 m
Concrete column	3 m	0.15 m	0.15 m
Cement plaster	-	-	20 mm x 10 mm
Glass window	8 m	0.13 m	3 mm
First floor - concrete	9 m	7.5 m	0.1 m
First floor - asbestos ceiling	9 m	7.5 m	4 mm
Asbestos roof	9 m	6.6 m	4 mm
Concrete overhang	9 m	1.2 m	0.1 m
Brick corridor	9 m	1 m	0.115 m

Table 8.11: Dimension of building materials for the SMSB classroom.

The standard air change rates for the classrooms were 2 ach^{-1} while that of the attic space was virtually 0 ach^{-1}. The air change rate of 2 was used to represent the worst-case scenario for the simulations at the design stage. In real buildings, these rates tended to be higher, which would then produce the advantage of having more desirable effects.

The different orientations representing the North-facing, South-facing, East-facing and West-facing walls were considered and simulated for monthly air temperature averages. This means that the SMSB classroom was simulated with one reference wall facing North, and then the whole classroom was rotated through South-facing, East-facing and West-facing directions. This was made to ascertain similarities or otherwise in the predicted internal air temperatures in the classroom. It was then found that since the materials were the same, the simulated air temperatures in the classroom of the SMSB did not change significantly in all of these permutations after all. Results of this cursory permutations are shown in Table 8.12:

Zone 1	zone1-NS (C)	zone1-SN (C)	zone1-EW (C)	zone1-WE (C)	% diff (N-S)	% diff (E-W)	%diff (N-W)	% diff (S-E)
JAN	25.69	25.69	25.70	25.70	0.00	0.00	-0.04	-0.04
FEB	25.80	25.80	25.84	25.84	0.00	0.00	-0.15	-0.15
MAR	26.28	26.28	26.39	26.39	0.00	0.00	-0.42	-0.42
APR	26.05	26.05	26.16	26.16	0.00	0.00	-0.42	-0.42
MAY	26.62	26.62	26.68	26.68	0.00	0.00	-0.23	-0.23
JUN	26.48	26.47	26.51	26.51	0.04	0.00	-0.11	-0.15
JUL	26.53	26.53	26.58	26.58	0.00	0.00	-0.19	-0.19
AUG	25.72	25.72	25.80	25.80	0.00	0.00	-0.31	-0.31
SEP	26.21	26.21	26.33	26.33	0.00	0.00	-0.46	-0.46
OCT	26.41	26.41	26.49	26.49	0.00	0.00	-0.30	-0.30
NOV	25.90	25.90	25.92	25.92	0.00	0.00	-0.08	-0.08
DEC	25.41	25.42	25.42	25.42	-0.04	0.00	-0.04	0.00
Ave	26.09	26.09	26.15	26.15	0.00	0.00	-0.23	-0.23
Zone 2	zone2-NS (C)	zone2-SN (C)	zone2-EW (C)	zone2-WE (C)	% diff (N-S)	% diff (E-W)	% diff (N-W)	% diff (S-E)
JAN	28.21	28.21	28.21	28.21	0.00	0.00	0.00	0.00
FEB	28.36	28.36	28.36	28.36	0.00	0.00	0.00	0.00
MAR	29.38	29.38	29.38	29.38	0.00	0.00	0.00	0.00
APR	28.85	28.85	28.85	28.85	0.00	0.00	0.00	0.00
MAY	29.70	29.70	29.70	29.70	0.00	0.00	0.00	0.00
JUN	29.33	29.33	29.33	29.33	0.00	0.00	0.00	0.00
JUL	29.47	29.47	29.47	29.47	0.00	0.00	0.00	0.00
AUG	28.28	28.28	28.28	28.28	0.00	0.00	0.00	0.00
SEP	29.13	29.13	29.13	29.13	0.00	0.00	0.00	0.00
OCT	29.46	29.46	29.46	29.46	0.00	0.00	0.00	0.00
NOV	28.35	28.35	28.35	28.35	0.00	0.00	0.00	0.00
DEC	27.57	27.57	27.57	27.57	0.00	0.00	0.00	0.00
Ave	28.84	28.84	28.84	28.84	0.00	0.00	0.00	0.00
Zone 3	zone3-NS (C)	zone3-SN (C)	zone3-EW (C)	zone3-WE (C)	% diff (N-S)	% diff (E-W)	% diff (N-W)	% diff (S-E)
JAN	27.21	27.21	27.22	27.22	0.00	0.00	-0.04	-0.04
FEB	27.34	27.34	27.39	27.39	0.00	0.00	-0.18	-0.18
MAR	28.06	28.06	28.19	28.19	0.00	0.00	-0.46	-0.46
APR	27.71	27.71	27.83	27.83	0.00	0.00	-0.43	-0.43
MAY	28.49	28.49	28.56	28.56	0.00	0.00	-0.25	-0.25
JUN	28.25	28.25	28.29	28.29	0.00	0.00	-0.14	-0.14
JUL	28.34	28.34	28.40	28.40	0.00	0.00	-0.21	-0.21
AUG	27.24	27.24	27.34	27.34	0.00	0.00	-0.37	-0.37
SEP	27.93	27.93	28.07	28.07	0.00	0.00	-0.50	-0.50
OCT	28.22	28.22	28.31	28.31	0.00	0.00	-0.32	-0.32
NOV	27.44	27.44	27.46	27.46	0.00	0.00	-0.07	-0.07
DEC	26.77	26.77	26.77	26.77	0.00	0.00	0.00	0.00
Ave	27.75	27.75	27.82	27.82	0.00	0.00	-0.25	-0.25

Table 8.12: Simulated monthly air temperatures for the original design and materials for an SMSB classroom showing values and percent differences between the combinations of orientations. Orientations of the walls were N - North-facing; S - South-facing; E - East-facing; W - West-facing.

Table 8.12 shows results for the monthly simulated air temperatures in the SMSB classrooms orientated along the North-South and East-West longitudinal axes. In all the zones, i.e. zone 1 (ground floor), zone 2 (attic space) and zone 3 (first floor), it was found that the air temperatures in all three zones differed only slightly at less than 0.25 % if the classroom was rotated and made to face in all four directions of the compass. Thus, since the preferred layout of the SMSB classroom has traditionally been in the East-West facing direction, this orientation was also chosen as a basis for all other simulations. In addition the BiPV array generation on the roofs was also in this direction. Further simulations using this layout was then done for hourly values.

8.4.4 Preliminary findings

The first round of preliminary execution in SUNREL was made using the originally-designed building materials and architecture for hourly values. This gives a feel of the internal classroom temperature and would act as a basis and reference for further simulations. This round of preliminary simulations was named as Case 0. The thermal load, besides coming from the ambient, included gains from the occupants of the classroom during school hours at 100 W per person. The air change rate for the classrooms was set according to the standard regulations. Results of the simulations for Case 0 are shown in Table 8.13 and graphically illustrated in Figure 8.12:

Hr	zone 1 temperature (C)	zone 2 temperature (C)	zone 3 temperature (C)	Tamb (C)
1	26.0	26.0	27.0	24.5
2	25.8	25.7	26.8	24.2
3	25.7	25.5	26.5	24.0
4	25.5	25.3	26.3	23.8
5	25.4	25.1	26.1	23.6
6	25.2	25.0	25.9	23.5
7*	25.2	25.3	25.9	23.7
8*	25.2	26.9	26.2	25.2
9*	25.4	29.3	26.8	27.3
10*	25.6	31.7	27.6	29.0
11*	25.9	34.0	28.4	30.2
12*	26.1	35.3	29.0	30.9
13*	26.4	35.5	29.4	31.3
14*	26.6	34.8	29.7	31.2
15	26.8	33.2	29.6	30.7
16	26.9	31.5	29.4	29.9
17	26.9	30.1	29.2	29.0
18	26.9	28.9	28.9	28.0
19	26.8	27.9	28.5	27.0
20	26.7	27.5	28.3	26.2
21	26.6	27.1	28.0	25.7
22	26.4	26.8	27.7	25.3
23	26.3	26.5	27.5	25.0
24	26.1	26.2	27.3	24.7
Ave	26.1	28.8	27.8	26.8

Table 8.13: Case 0 hourly internal air temperature simulation for original SMSB design. zone 1 - ground floor; zone 2 - attic space; zone 3 - first floor. Average for the habitated classrooms in zones 1 and 3 = 26.95 °C. School hours are shown by *.

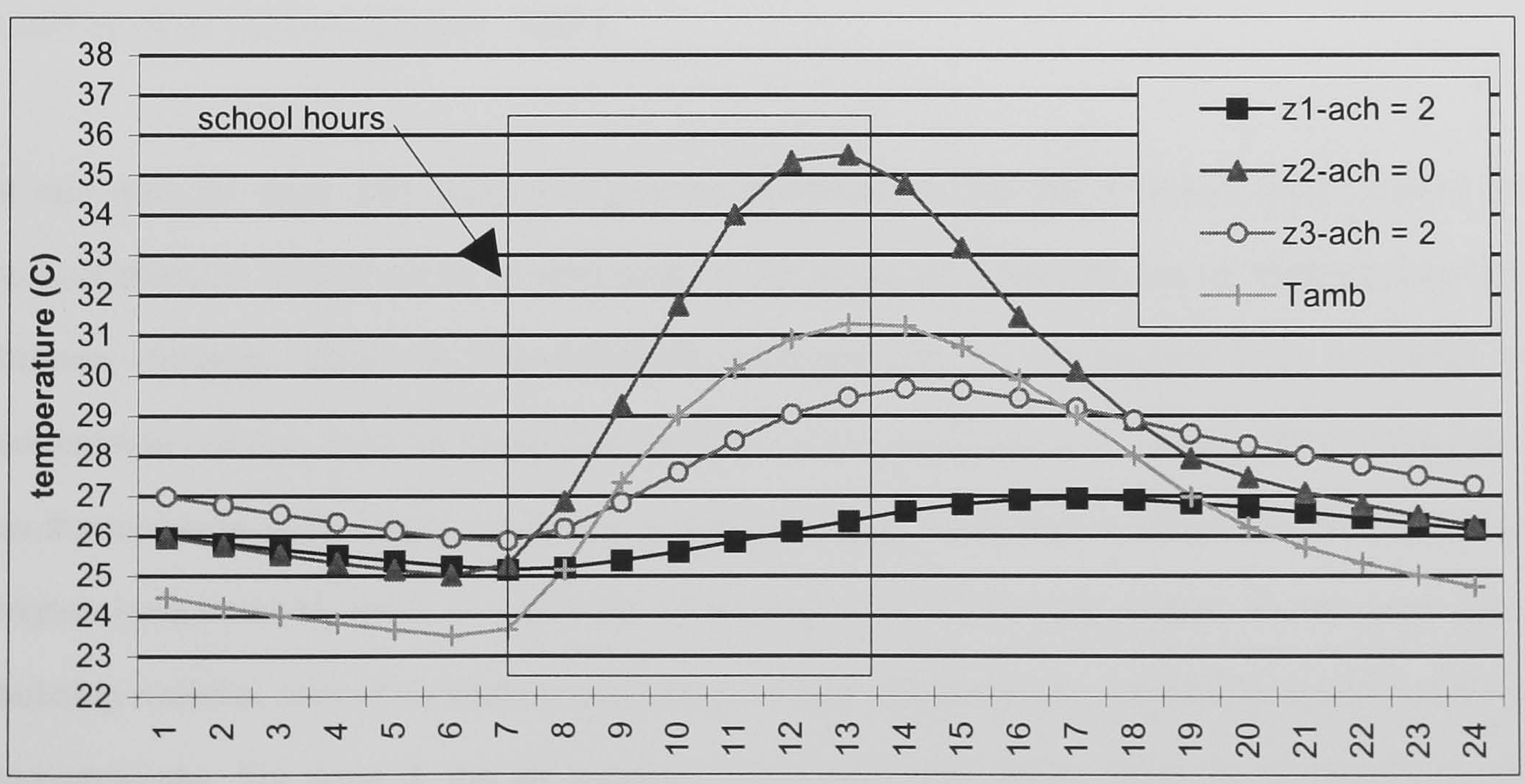


Figure 8.12: Graphical representation of Case 0 hourly internal classroom temperature for existing SMSB design. ach - air change per hour. School hours from 0730 - 1330.

Results from Case 0 as shown in Table 8.13 depict the simulated values from this preliminary execution for the existing original SMSB design. The average air temperature in the habitated classroom space (zone 1 and zone 3) was about 27 °C from the simulations. An earlier monitoring work done in Malaysian schools revealed that the measured average classroom temperature was about 28 °C (Inangda, 1990) which gives a difference of about 1.8 % from the simulated results of this research. However, those measurements were made in schools located inside the capital city, in Kuala Lumpur, which is expected to be hotter than in rural areas. This is the main reason anticipated for the slightly higher measured temperatures.

The higher attic air space temperatures in zone 2 by using the existing SMSB design as in Case 0, will pose a serious threat to the PV cells. This is because the attic air space with a higher temperature will subsequently elevate the operating temperature of the PV cell much higher, and this will deteriorate their performance as well as shorten their lives. This is evident as the hourly average temperatures in zone 2 reached in excess of 35 °C which then provides an elevated temperature to the back of the integrated modules. With further temperature rises from solar radiation, the PV cell temperatures may reach up to 20 to 40 degrees higher than the ambient and may reach in excess of 75 °C. This experience was learnt from the BiPV-WHF installation as well as cited by other workers (Dichler, 1997).

It can also be seen that using the original materials for the SMSB gives much higher internal temperatures in all the zones as compared to the accepted temperatures for comfort zone for mid-latitude climates. However, the simulated temperatures in the ground floor is closer to the acceptable comfort zone for Malaysians at 28.2 °C (Abdulshukor and Young, 1993). This is evident as the temperature in zone 1 ranged from about 25 to 27 °C during the school hours. Zone 3 suffers higher temperatures more so because of its proximity to the attic space, whose very nature of building material, lack of ventilation and direct contact with the solar radiation produced much higher temperatures. For zone 3, the air temperature ranged from about 26 to 30 °C during the school hours. Focus was then given in further simulations to lower the temperatures in zone 3 (first floor) by varying the ceiling material and air change rates of the attic space, within practical anticipation of possible application. Results of these further combinatorial simulations are shown in Table 8.14:

Case	ach^{-1}	roof	ceiling	ΔT zone1	% diff zone1	ΔT zone2	% diff zone2	ΔT zone3	% diff zone3
Case 0	0.1	asb	asb	0.00	0.00	0.00	0.00	0.00	0.00
Case 1	2.0	asb	con	0.07	0.27	1.24	3.50	1.33	4.51
Case 2	10	asb	con	0.08	0.29	1.69	4.80	1.41	4.79
Case 3	20	asb	con	0.07	0.26	2.08	5.95	3.06	10.71
Case 4	20	clay	bric	0.11	0.43	1.56	4.43	1.34	4.58
Case 5	20	asb	con	0.08	0.30	2.11	6.03	1.43	4.86
Case 6	-	-	con	0.09	0.35	0.89	3.00	-	-
Case 7	30	asb	con	0.08	0.30	2.39	6.86	1.43	4.86
Case 8	2.0	asb	asb	0.01	0.02	0.18	0.50	0.10	0.32
Case 9	0	asb	con	0.07	0.25	1.07	3.03	1.30	4.42
Case 10	0.1	asb	con	0.07	0.26	1.08	3.05	1.30	4.42

Table 8.14: Temperature differences referenced to Case 0 due to variation of air change rates and building materials. Case 0 - original SMSB design. Case 6 assumes no attic space. Positive values indicate drop in temperature. ach^{-1} - air change per hour; asb - asbestos; con - concrete.

Table 8.14 shows the temperature predictions of different case studies. The values show the temperature drop experienced in the different case studies from the original design as in Case 0. It can be seen that the most promising results come from Case 3. In Case 3 the ceiling material was replaced by standard 100 mm concrete with a rate of 20 ach^{-1}. Its effect is shown by having the highest percentage drop of temperature of about 11 % in zone 3. These effects are shown graphically in Figure 8.13 and 8.14:

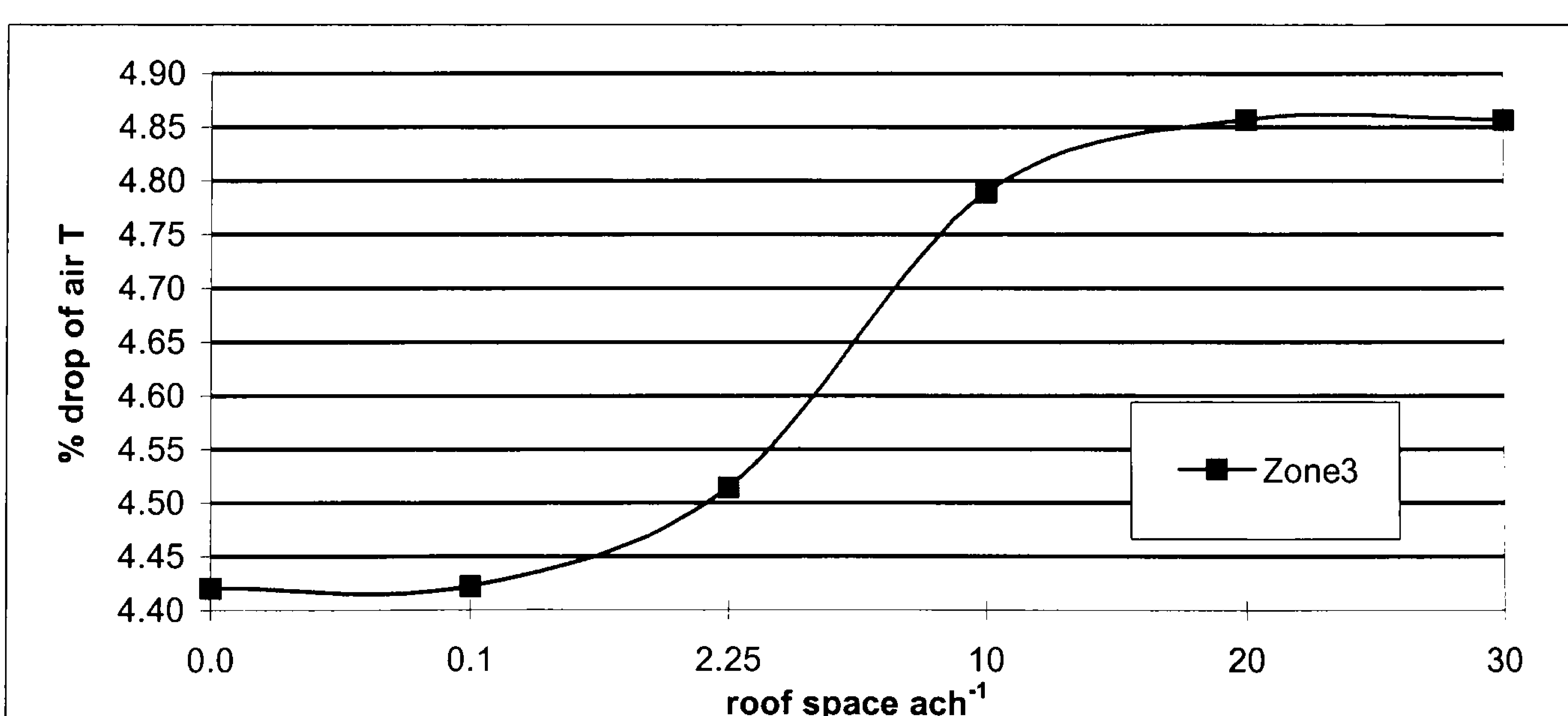


Figure 8.13: Case 3 variation of air temperature in zone 3 (first floor) as a function of attic space ach^{-1}. The optimum value for zone 3 is by having an ach^{-1} = 20 in the attic space. This maximises the temperature drop in zone 3.

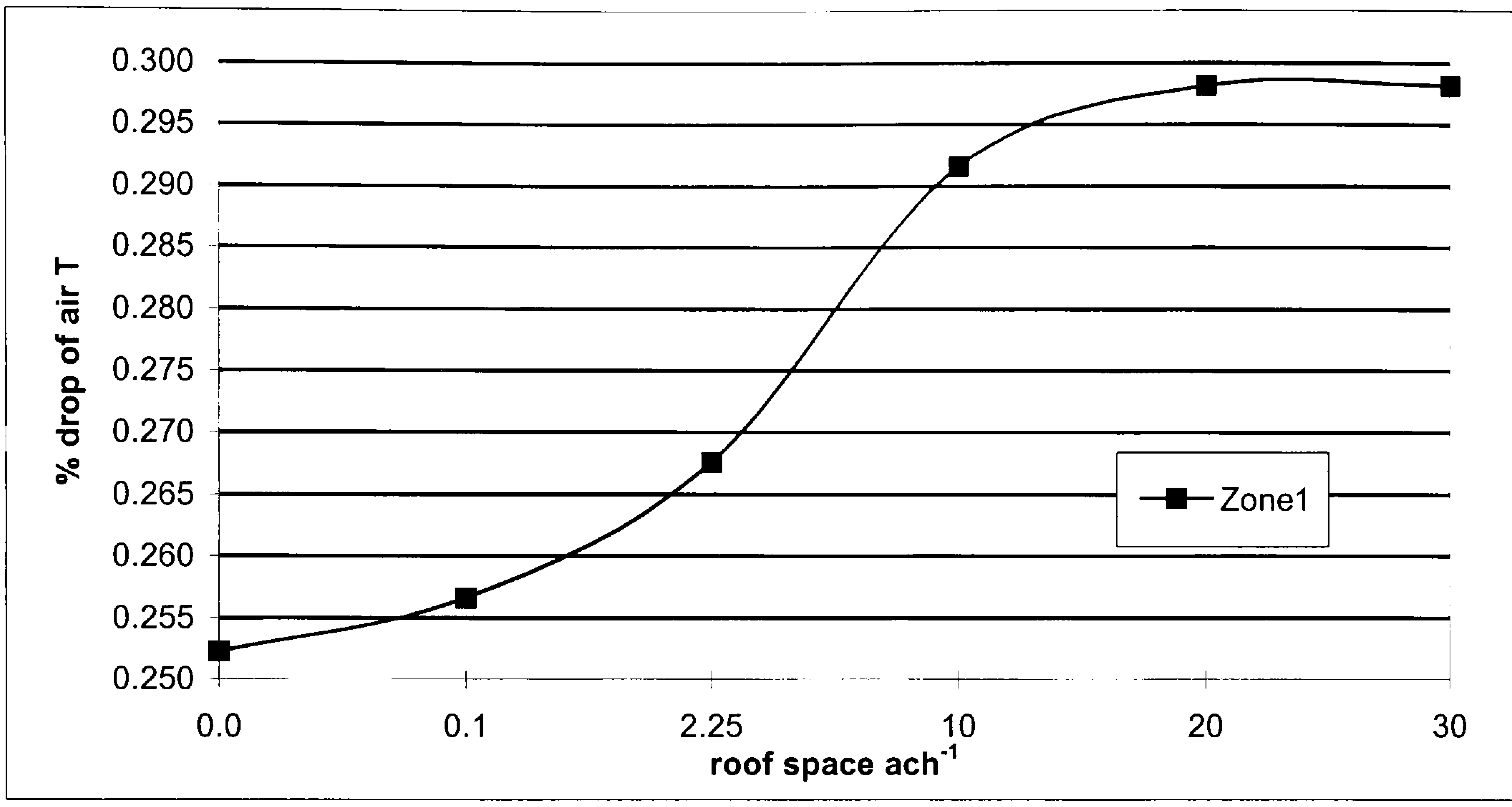


Figure 8.14: Case 3 variation of air temperature in zone 1 (ground floor) as a function of attic space ach^{-1}. The optimum value for zone 3 is by having an ach^{-1} = 20 in the attic space. Clearly the benefits are less for zone 1 as compared to zone 3 (shown in Figure 8.13).

Figure 8.13 shows that the effects of changing the air change rate in zone 2 (the attic air space), on zone 3. Specifically, the air temperature in zone 3 is desirably affected by the different air change rates in zone 2. By varying the air change rate in zone 2, the air temperature in zone 3 dropped by up to about 5 % from the values in the original design as in Case 0.

Figure 8.14 shows the same effects as experienced by zone 1. However, the desirable effect is only minimal with a drop of up to about 0.3 %. Again, with the heavier thermal mass, a longer distance from zone 2, and that zone 1 is also naturally ventilated, the effects of varying the air change rate in zone 2 is not felt significantly by zone 1.

Thus Case 3 shows to be the most optimum for the integration of the PV arrays as well as for the internal air temperature for the classroom in the first floor. This provides a lower base temperature for the PV arrays and lowers the internal classroom air temperature to be closer to the comfort air temperature. However for Case 3, the cost-effectiveness of having an air change rate of 20 ach^{-1} or above as in Case 7, even if being powered by the BiPV installation is questionable.

An alternative option is to use Case 8, which uses the same original SMSB as in Case 0 design, except for the air change rate which is set at 2 ach^{-1}. This corresponds very much to having the attic air space naturally ventilated as well, along with the Malaysian standard for the ground floor and the first floor of the SMSB. However, the temperature drop in the zones of interest, i.e. zones 1, 2 and 3 are all very minimal. This situation again, does not improve the performance of the BiPV cells.

Thus having considered the options, it was decided that the most practical solution would be to use Case 1 as the optimum solution. Case 1 used 100 mm concrete as the ceiling for zone 3 and having an air change rate of 2 ach^{-1} in the attic space. The effects for Case 1 are shown in Table 8.14 in which the air temperature dropped by about 4.5% in zone 3 and an air temperature drop of about 3.5 % in zone 2. This means that zone 3 (the first floor) and zone 2 (attic space) air temperatures would be lowered considerably in a compromising way and would in turn improve the general performance of the BiPV array on its roof. Thus the SMSB classroom would have the ceiling of the first floor changed to standard concrete, and the air change rate in the attic space be naturally ventilated at 2 ach^{-1}.

These preliminary findings provide a rough guide as to the ranges of air temperatures the PV arrays will be experiencing as a consequence of their being integrated in the SMSB roof design. As a synergistic benefit, the air temperatures of the habitated classroom have also been predicted as a result of the design alteration targeted at optimising the BiPV installation. The set-up and results of the final simulation for Case 1 are presented and discussed in the next Chapter.

Chapter 9. BiPV-SMSB: Final Simulation Results, Analysis and Discussions

9.1 Final BiPV-SMSB simulation execution

The final BiPV-SMSB set-up in PVSYST 2.0 was basically similar to the preliminary execution. The set-up for the final execution of the BiPV-SMSB classroom simulation was designed with eighteen PV modules integrated on the East-facing roof and another eighteen modules integrated on the West-facing roof. The PV modules were connected in a six by six string combination, i.e. there were six modules connected in series in one string, with six strings connected together in parallel per SMSB classroom. The array comprised of the Siemens M55 PV modules and thus gave an array output of 18.6 A DC and an array voltage of 104.4 V DC. The peak power rating was 1.9 kWp per SMSB classroom, grid-interactive via an SMA PV-WR1800 inverter. This approximates the electrical energy requirement per class ratio of 2,745 kWh and thereby attempts to minimise the importation of electrical energy from the grid. The total integrated BiPV array covers up about 15 m^2 of a possible 118 m^2 of total roof area, which gives about 13 % coverage. The density of the existing standard asbestos roof is between 10 to 17 kgm^{-2} whilst the density of the Siemens M55 modules is 13 kgm^{-2}. Thus the loading of the PV modules onto the existing structure of the SMSB design is within the safety limits as stipulated in the Building By-Laws. A 3-D geometric sketch of the set-up for the final simulation set-up is best illustrated in Figures 9.1, 9.2 and 9.3:

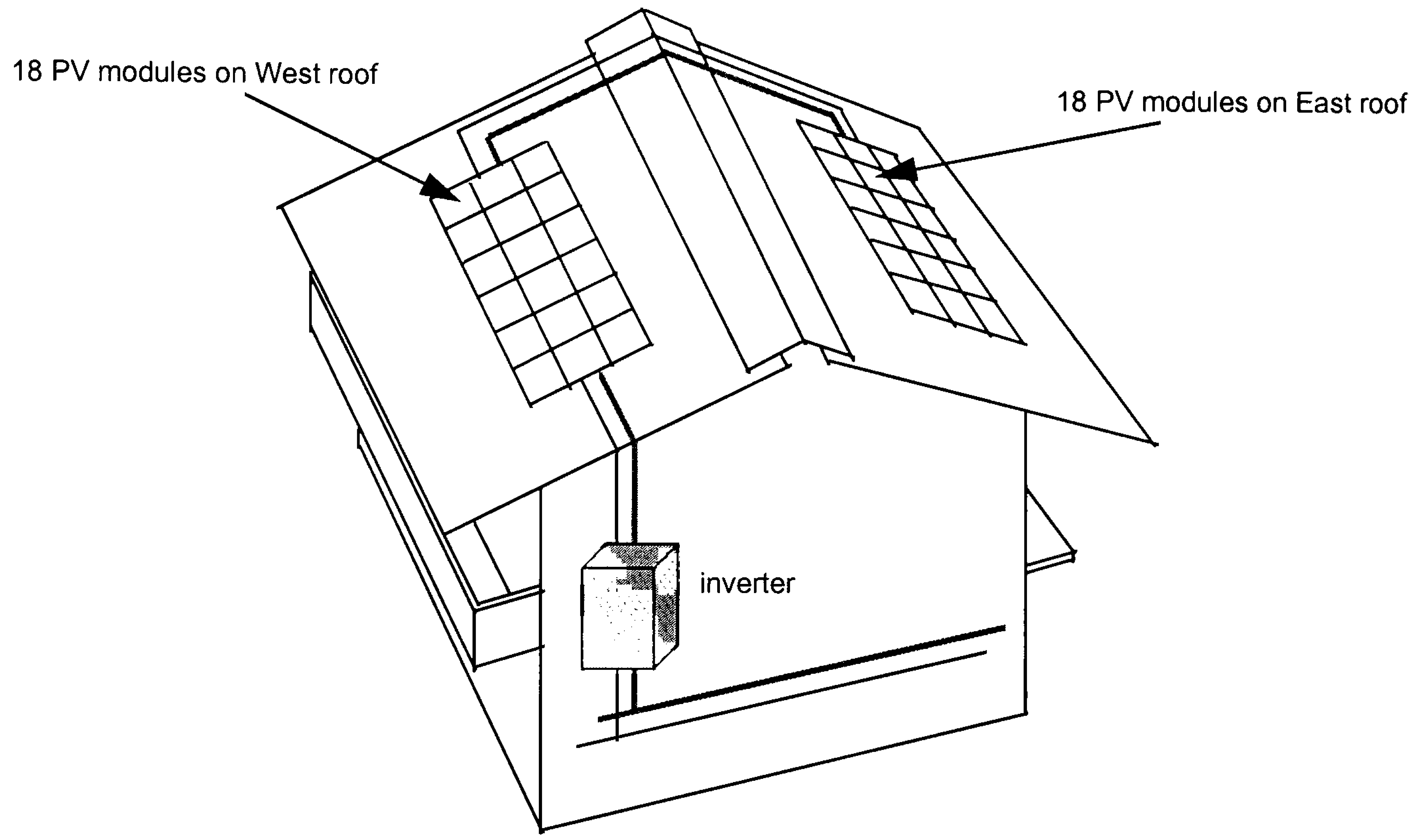


Figure 9.1: A 3-D schematic geometrical representation of the final BiPV-SMSB classroom simulation set-up in PVSYST 2.0.

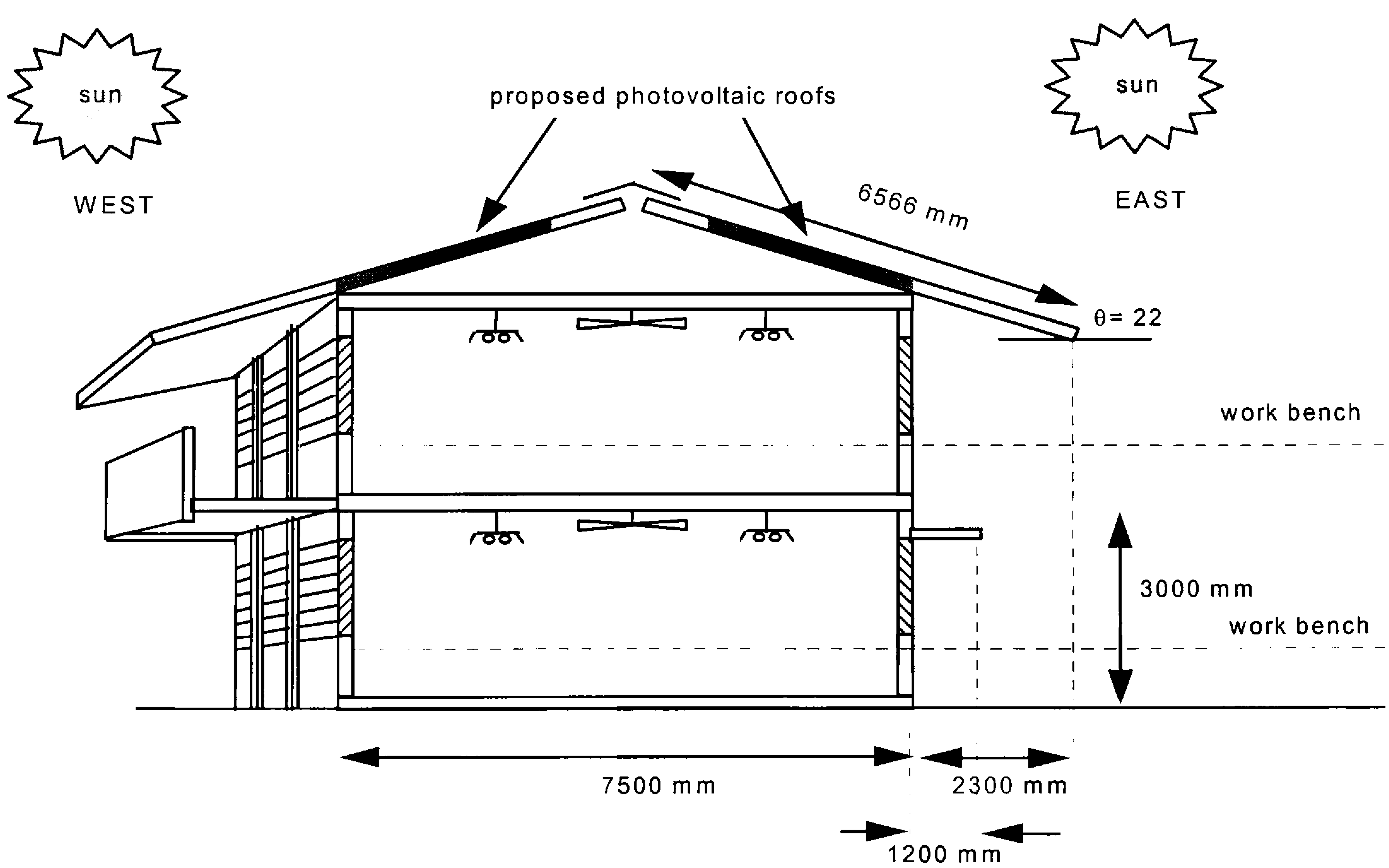


Figure 9.2: Cross-sectional view of final BiPV-SMSB classroom simulation set-up in PVSYST 2.0.

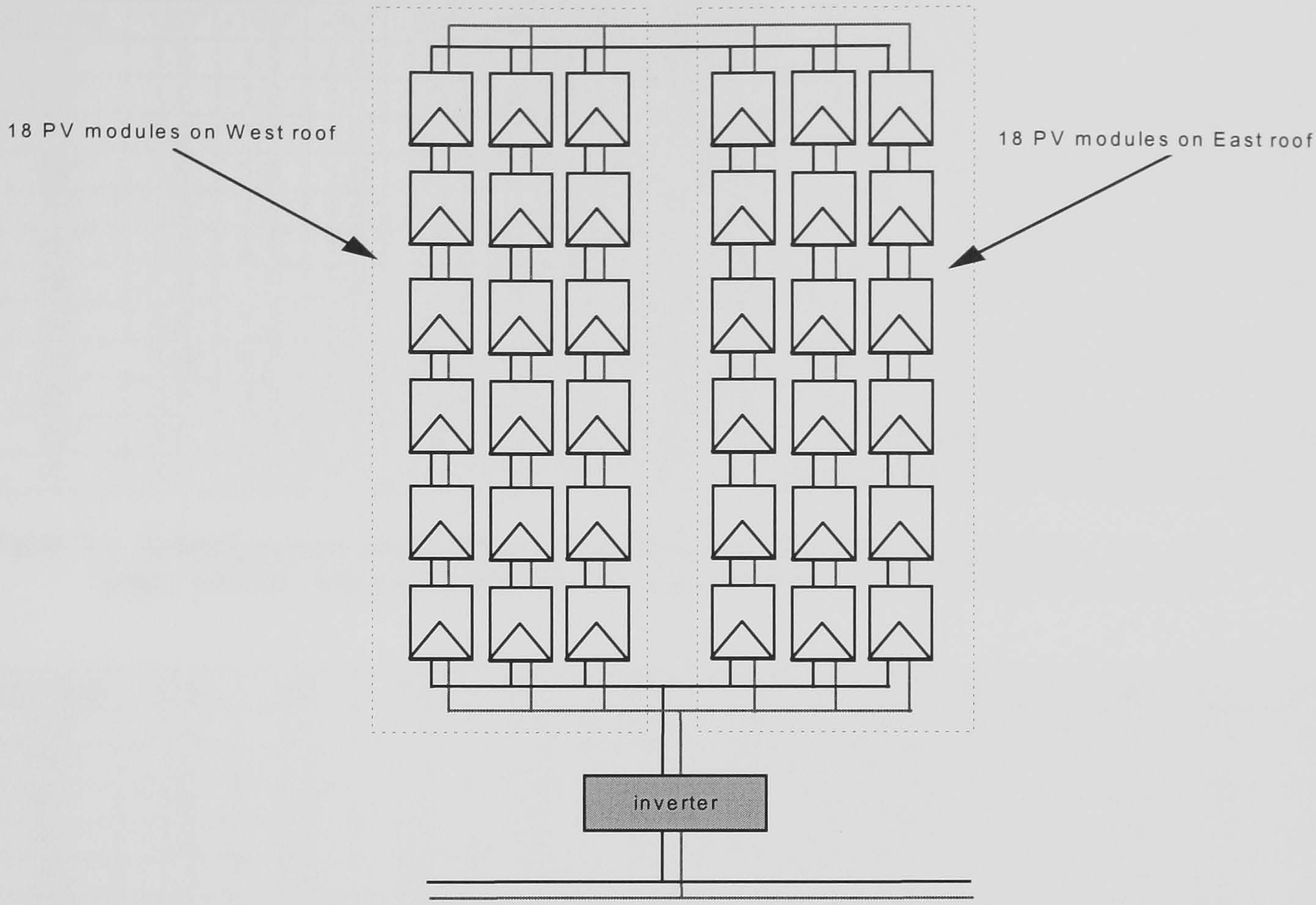


Figure 9.3: Wiring circuit diagram for the final BiPV-SMSB classroom simulation set-up in PVSYST 2.0.

The roofs were ventilated with an air change rate of 2 ach^{-1}. This was achieved at the apex of the roof by installing an elevated ridge to provide natural ventilation so as to minimise the adverse effects of high temperatures of the cells, as discussed in an earlier Chapter.

9.2 Results, analysis and discussions

9.2.1 Array shading

The PV modules on both the East and West-facing roofs suffered minimal shading corresponding to the architectural build-up of the building itself. The shading coefficient values for the BiPV arrays on these roofs are shown in Tables 9.1 and 9.2:

Hgh\Azi	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°
110°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
100°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
90°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
80°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
70°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
60°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
50°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
40°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
30°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
20°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	Behind	Behind	Behind	Behind
0°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	Behind	Behind	Behind	Behind	Behind

Table 9.1: Shading factors on the East-facing BiPV roof. Hgh - sun height angle; Azi - sun azimuth angle. Behind - this means that the sun was coming from the back of the modules.

Hgh\Azi	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°
110°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
100°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
90°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
80°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
70°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
60°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
50°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
40°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
30°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
20°	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10°	Behind	Behind	Behind	Behind	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0°	Behind	Behind	Behind	Behind	Behind	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 9.2: Shading factors on the West-facing BiPV roof.

Table 9.1 and 9.2 show the shading factors on the East-facing and West-facing BiPV arrays. The height of the sun (Hgh) is shown in degrees from the horizontal at 0° to a peak of 110°. The azimuth (Azi) position of the sun due South is shown by an angle of 0°, the East by the angles 20° to 120° and the West by the angles -20° to -120°. These values are best illustrated graphically, shown in Figures 9.4 and 9.5:

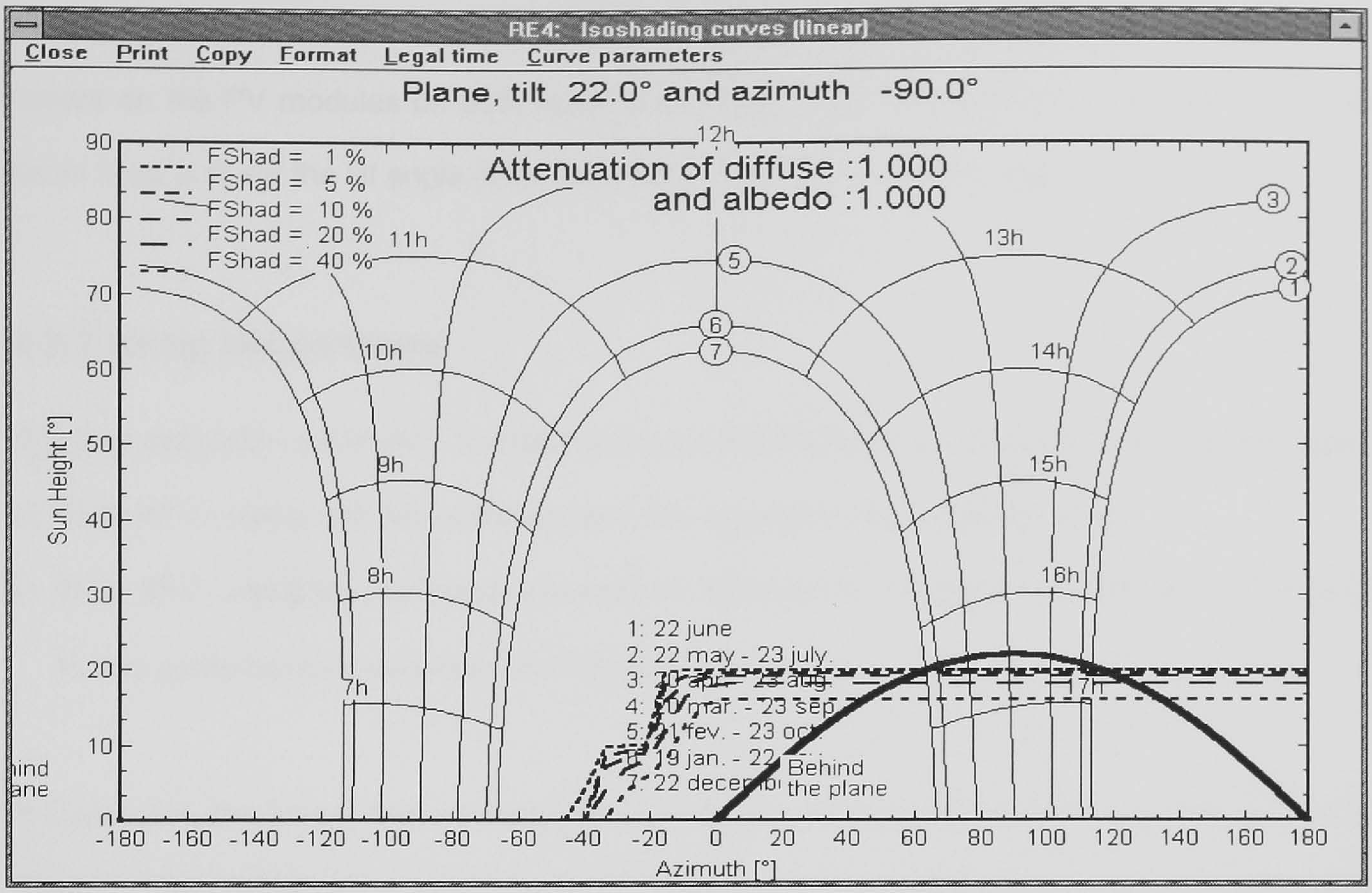


Figure 9.4: Graphical output of shading factor on the East-facing BiPV roof. The area under the dotted and heavy solid lines show the extent of shading on the modules.

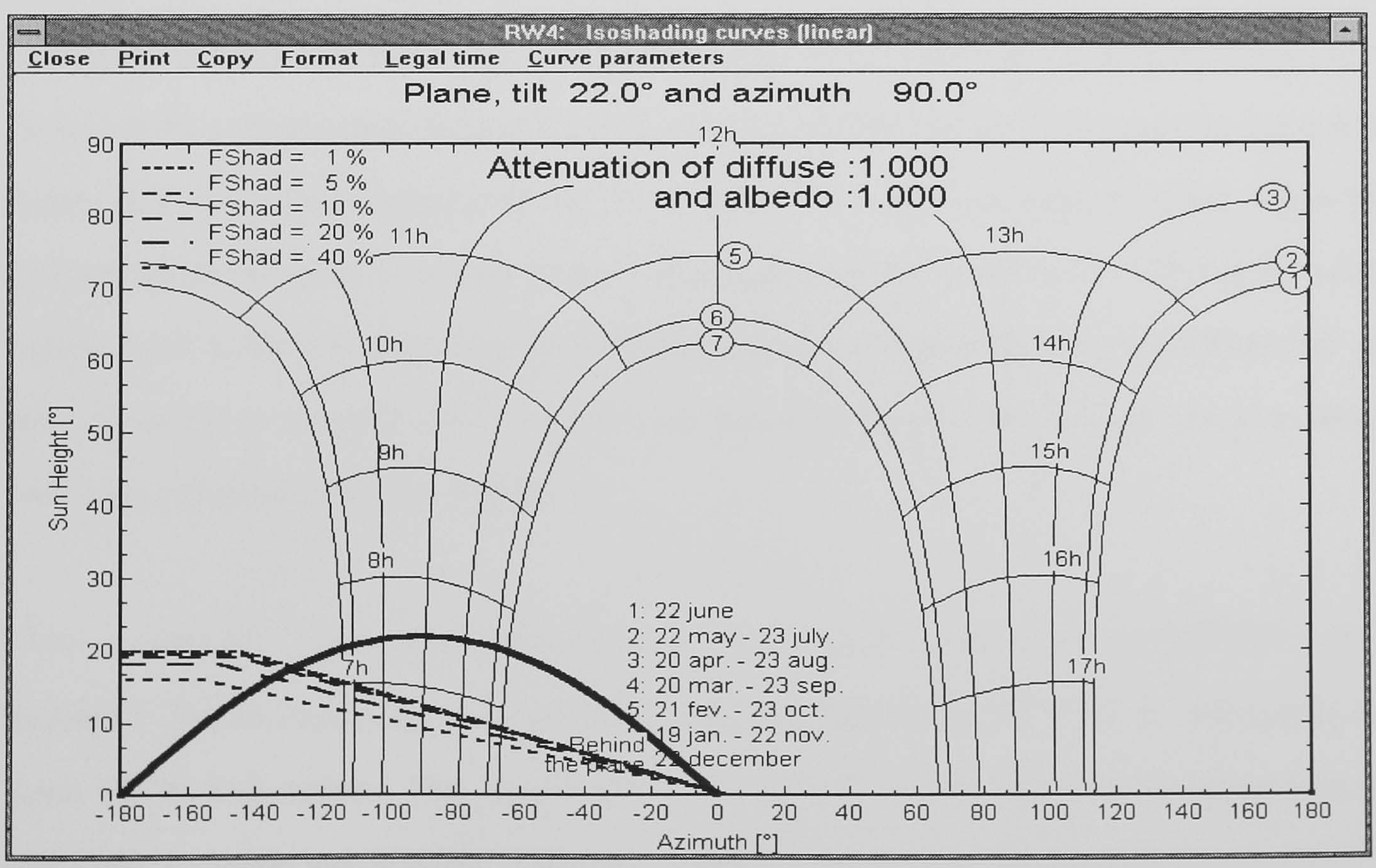


Figure 9.5: Graphical output of shading factor on the West-facing BiPV roof. Again, the shading extent on the modules are minimal.

Clearly, from the values in Tables 9.1, 9.2 and Figures 9.4 and 9.5, it can be seen that the shading factors on the PV modules on both roofs are minimal. The only way left to eliminate the shading factor lines is to set the tilt angle of the BiPV at 0° from the horizontal, which is impractical.

9.2.2 Array temperature

The final simulation executions to obtain the system performance output were done in two ways:

a) Case 4PV - using met data comprising of the actual ambient air temperature.
b) Case 5PV - using the roof space elevated air temperature simulated by SUNREL 1.0β as a basis for the performance calculations in PVSYST 2.0.

In Case 4PV, the final simulation executions used the recorded ambient air temperature as a basis for the system performance calculations. This means that the Malaysian met data was input directly into PVSYST 2.0 and the set-up was then executed in any normal way. However, the thermal simulations done in an earlier Chapter using SUNREL 1.0β showed that the air temperature in the attic space of the SMSB design was considerably higher than the ambient air temperature (Case 1). Since the PV modules were integrated on the roof of the SMSB design, it was decided that another option of final simulation executions had to be used, in an effort to incorporate this higher than ambient air temperature in the attic space. The rationale for this is due to the fact that the system performance of the PV array depends negatively on temperature rise. This experience has also been illustrated in the BiPV-WHF installation as discussed in an earlier Chapter and is in tandem with the conclusions drawn for the site.

Thus, in Case 5PV, firstly, the air temperature in the attic space was simulated by SUNREL 1.0β, as in Case 1. This roof space elevated air temperature was then fed into PVSYST 2.0 and served as a basis for its calculations. This means that PVSYST 2.0 system performance simulations are enhanced by using the SUNREL 1.0β attic space air temperature simulations. Thus Case 5PV would produce more realistic system performances of the PV array, due to the increased temperature of the attic space and the system performance is thus anticipated to be lowered. Results from both, Case 4PV and Case 5PV are shown in Tables 9.3 and 9.4:

Month	GlobHor kWh/m²	T Amb °C	TArray °C	EOutInv kWh	EffArrR %	EffSyR %	EffInvR %	PR %	Monthly yield $kWhd^{-1}$ kWp^{-1}
Jan	158	26.4	42.8	210	10.2	8.9	87.9	68.8	3.4
Feb	156	26.8	44.0	206	10.1	8.9	87.9	68.5	3.7
Mar	180	27.1	43.4	239	10.2	9.0	87.9	69.4	3.9
Apr	175	27.2	43.5	232	10.2	9.0	87.8	69.2	3.9
May	165	27.4	41.7	220	10.3	9.0	87.8	69.5	3.6
Jun	153	27.3	40.7	204	10.3	9.1	87.8	69.8	3.4
Jul	158	26.9	40.1	212	10.3	9.1	87.7	69.9	3.5
Aug	158	26.9	40.1	211	10.3	9.1	87.7	69.9	3.4
Sep	153	26.7	40.7	204	10.3	9.0	87.8	69.6	3.4
Oct	154	26.6	40.1	206	10.3	9.1	87.7	69.7	3.4
Nov	134	26.3	40.5	177	10.2	8.9	87.7	68.7	3.0
Dec	136	26.3	40.8	179	10.1	8.9	87.5	68.1	2.9
Tot/ave	1882	26.8	41.5	2499	10.3	9.0	87.8	69.3	3.5

Table 9.3: System performance of BiPV for Case 4PV - using ambient air temperatures. GlobHor - global horizontal irradiation; TAmb - ambient temperature; TArray - array temperature; EOutInv - energy output from inverter; EffArrR - efficiency of array; EffSyR - efficiency of system; PR - Performance Ratio.

Month	GlobHor kWh/m²	T Roof °C	TArray °C	EOutInv kWh	EffArrR %	EffSyR %	EffInvR %	PR %	Monthly yield $kWhd^{-1}$ kWp^{-1}
Jan	158	28.2	44.5	205	9.9	8.7	87.9	67.1	3.3
Feb	156	28.4	45.8	199	9.8	8.6	87.8	66.4	3.6
Mar	180	29.4	45.9	237	10.1	8.9	88.0	68.7	3.9
Apr	175	28.9	45.3	231	10.2	8.9	88.0	68.9	3.9
May	165	29.7	44.0	218	10.2	9.0	87.8	69.0	3.5
Jun	153	29.4	43.3	201	10.2	8.9	87.8	68.7	3.4
Jul	158	29.5	42.8	209	10.2	9.0	87.8	69.1	3.4
Aug	158	28.3	41.8	210	10.3	9.0	87.8	69.4	3.4
Sep	153	29.2	43.3	202	10.2	8.9	87.8	68.8	3.4
Oct	154	29.5	43.1	201	10.1	8.8	87.8	68.1	3.3
Nov	134	28.4	42.6	175	10.1	8.8	87.6	67.9	2.9
Dec	136	27.6	42.0	177	10.0	8.8	87.7	67.6	2.9
Tot/ave	1882	28.9	43.7	2465	10.1	8.9	87.8	68.3	3.4

Table 9.4: System performance of BiPV for Case 5PV - using simulated attic space air temperature. T Roof - roof space air temperature.

The values in Tables 9.3 and 9.4 clearly show that the effects of using the ambient temperature and the attic space temperature altered the performance of the PV array. In general, the yearly yield dropped by about 2 %. The variations in values between Table 9.3 and 9.4 are shown in Table 9.5:

Month	T Roof °C	TArray °C	EOutInv kWh	EffArrR %	EffSyR %	EffInvR %	PR %	Monthly yield %
Jan	6.6	3.9	-2.3	-2.4	-2.6	-0.1	-2.6	-2.3
Feb	5.9	4.0	-3.2	-3.1	-3.2	-0.1	-3.1	-3.2
Mar	8.3	5.7	-0.9	-1.1	-0.9	0.1	-1.0	-0.9
Apr	6.0	3.9	-0.5	-0.7	-0.5	0.2	-0.4	-0.5
May	8.1	5.4	-0.8	-0.9	-0.8	0.1	-0.7	-0.8
Jun	7.3	6.3	-1.4	-1.6	-1.6	0.1	-1.6	-1.4
Jul	9.1	6.6	-1.2	-1.3	-1.2	0.1	-1.2	-1.2
Aug	5.1	4.1	-0.5	-0.8	-0.7	0.1	-0.7	-0.5
Sep	9.1	6.1	-1.4	-1.2	-1.2	0.0	-1.2	-1.4
Oct	10.2	7.2	-2.3	-2.5	-2.5	0.1	-2.4	-2.3
Nov	7.6	5.2	-1.2	-1.1	-1.2	-0.1	-1.2	-1.2
Dec	4.9	3.1	-0.9	-1.0	-0.8	0.2	-0.7	-0.9
Tot/ave	7.4	5.2	-1.4	-1.5	-1.4	0.1	-1.4	-1.4

Table 9.5: Variations of system performance due to temperature difference by switching from Case 4PV to Case 5PV. Negative indicates percentage drop in performance.

As shown in Table 9.5, the roof space air temperature increased by about 5 to 10 % with a yearly average increase of 7.4 % as a result of switching the simulations from Case 4PV to Case 5PV. The array temperature then increased by about 3 to 7 % with a yearly average increase of 5.2 %. As a consequence, the system performance of the BiPV-SMSB system as shown by the monthly yield dropped by about 0.5 to 3.2 % with a yearly average drop of 1.4 %. The corresponding decreases in other parameters showing the system performance are shown in the other columns.

Although the final output from both simulations differed by a yearly average of only 1.4 %, the importance of this finding is related to the hourly array temperature, analogous to the BiPV-WHF experience. As an example, in Case 4PV, the hourly array temperature was found to peak at 65 °C when the true hourly ambient air temperature was 36.1 °C. In Case 5PV, with the same ambient air temperature, the peak roof space air temperature under the PV arrays was 46.3 °C making the array temperature peaking at 75.7 °C. Naturally, in Case 4PV, as the calculations in PVSYST 2.0 were based on the true ambient air temperature, the hourly array temperature was lower than that in Case 5PV, which used the more realistic attic space air temperature.

Fortunately, in using Case 5PV, this higher array temperatures did not occur many times or for prolonged periods. In fact, the simulations showed that this peak array temperature occurred only once on 6th. January at 1300 hours. Moreover, since the attic space was ventilated at 2 ach^{-1}, the hotter air underneath the PV arrays would more than likely be buoyed up through the vents of the elevated ridge. This would simultaneously induce cooler air into the attic space from the opening at the eaves of the roofs. This is in tandem with the published literature in the Australian BiPV experience. The distribution of array temperatures for the BiPV-SMSB simulation of Case 5PV is shown in Table 9.6:

Temperature range (^{o}C)	Frequency	% Occurrence
76 - 80	1	0.0
71 - 75	35	0.4
66 - 70	133	1.5
61 - 65	306	3.5
56 - 60	430	4.9
51 - 55	482	5.5
46 - 50	513	5.9
41 - 45	582	6.6
36 - 40	639	7.3
31 - 35	1141	13.0
26 - 30	2479	28.3
21 - 25	1919	21.9
16 - 20	100	1.1
< 15	0	0.0
Total	8760	100.0

Table 9.6: Percent occurrences of range of array temperatures in Case 5PV showing frequency of distribution.

From Table 9.6, it is clear that the array temperature peaked above 75 ^{o}C only once in the year. The array temperature ranged from 16 to 65 ^{o}C about 98 % of the time in a year. Thus the arrangement as in Case 5PV proves to be within a reasonable and practical design to produce the optimum performance from BiPV applications in the Malaysian school building design. Excessive array temperature is always a cause for concern mainly to the system performance and life of the PV cells. Thus adequate ventilation of the PV cells is seen as a major issue in its integration in the Malaysian built environment. This is the main reason that forced the attic space to be opened for ventilation as described and discussed in an earlier Chapter. In this respect, a good design of the integration is seen as crucial to Malaysian BiPV applications. Thus from this point onwards all the final BiPV-SMSB simulations present system performance results simulated by using the attic space air temperature as in Case 5PV.

Although in Case 5PV when the array temperature was higher, it did not reduce the system performance very hugely due to the smaller difference between the average ambient air temperature and the attic space air temperature. More detailed analysis from first principles revealed that the array temperatures and system performances are directly related to solar irradiance. Since the solar irradiance in the Malaysian simulation is of a considerable amount, it would seem to have a major role in determining the system performance. PVSYST 2.0 has been reported to over-predict the RMSE hourly irradiation values ranging from 5.1 % to 15.0 % (PVSYST 2.0 manual, 1996). Thus it follows that the algorithm for the hourly irradiation with an average of 10 % would have a bigger role in the simulations than array temperature alone. In this situation, the radiant factor in PVSYST 2.0 would seem to be in need of a review in further work.

9.2.3 System performance

9.2.3.1 Total PV energy

From the simulated results shown in Table 9.4, it can be seen that the total PV energy generated by the BiPV-SMSB classroom p.a. was 2,465 kWh. This is very close to the energy requirement per SMSB classroom which was 2,745 kWh. This means that theoretically, the total PV generation is within a 10 % range of being able to displace the electrical energy needs. However, a more realistically practical assumption means that the BiPV generation is more than likely to be able to meet this requirement totally.

9.2.3.2 Final yield

The final yield p.a. was 1,245 $kWhkWp^{-1}$. This is considered excellent and is very close to the guideline as given in the literature (EUDG XVII, 1993) but is lower than the Australian BiPV applications.

9.2.3.3 Array yield

The array yield p.a. was 3.4 $kWhd^{-1}kWp^{-1}$. Again this is considered excellent with the EU guideline but lower than the Australian applications.

9.2.3.4 Array, system and inverter efficiencies

The simulated PV array conversion efficiency was about 10 % and the system efficiency was about 9 %. These values have been anticipated and they are higher than most of those listed in the literature. The simulated inverter efficiency was about 88 %.

9.2.3.5 Performance Ratio

The simulated PR was about 68 % p.a. This can be attributed to the higher operating temperature of the PV arrays themselves. Thus the issue of controlling the operating temperature of the PV arrays is of real importance in these types of climate applications.

The monthly system performance results presented in the preceding sections are graphically represented in Figures 9.6 and 9.7:

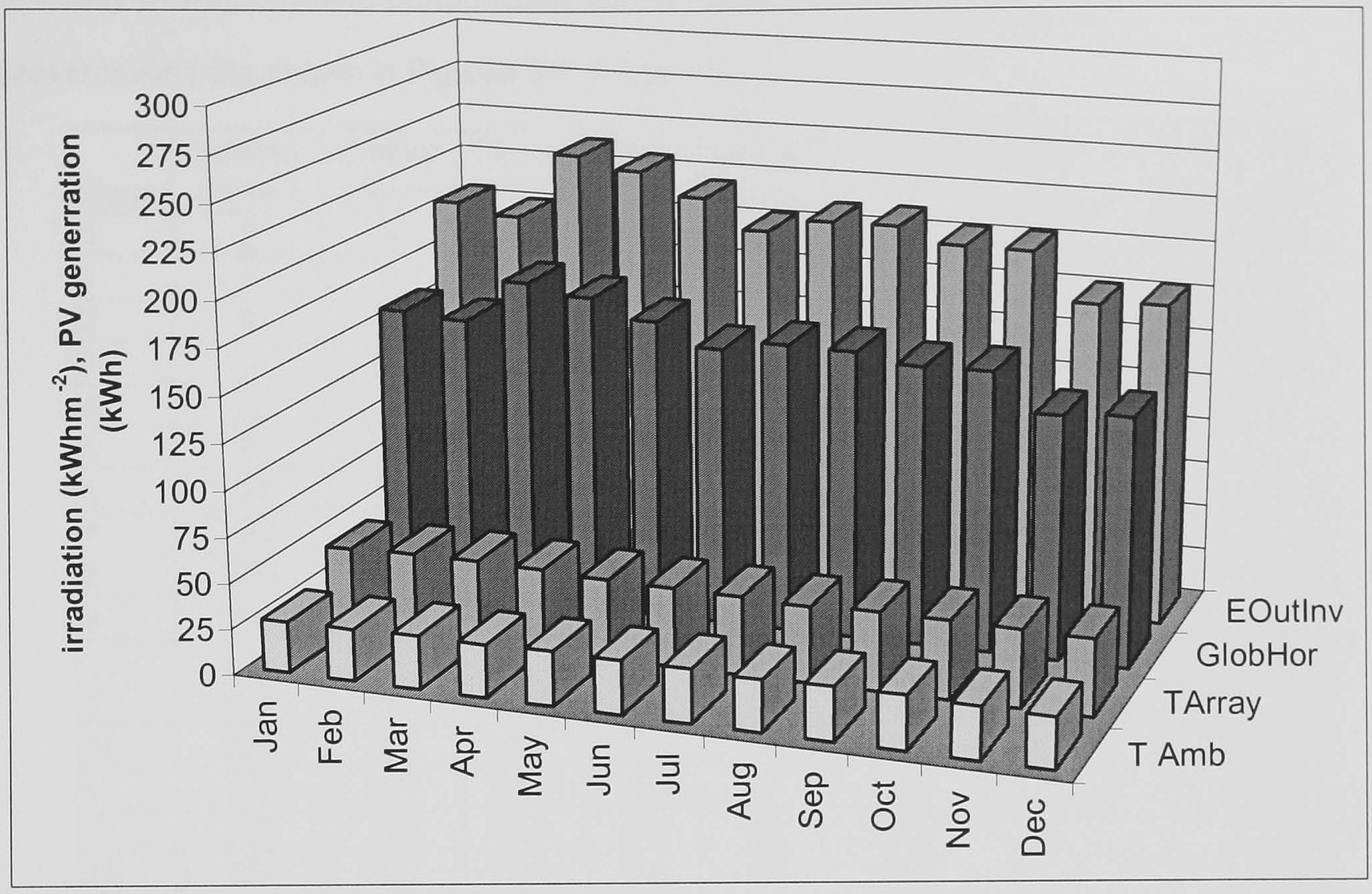


Figure 9.6: Graphical output of monthly system performance for Case 5PV.

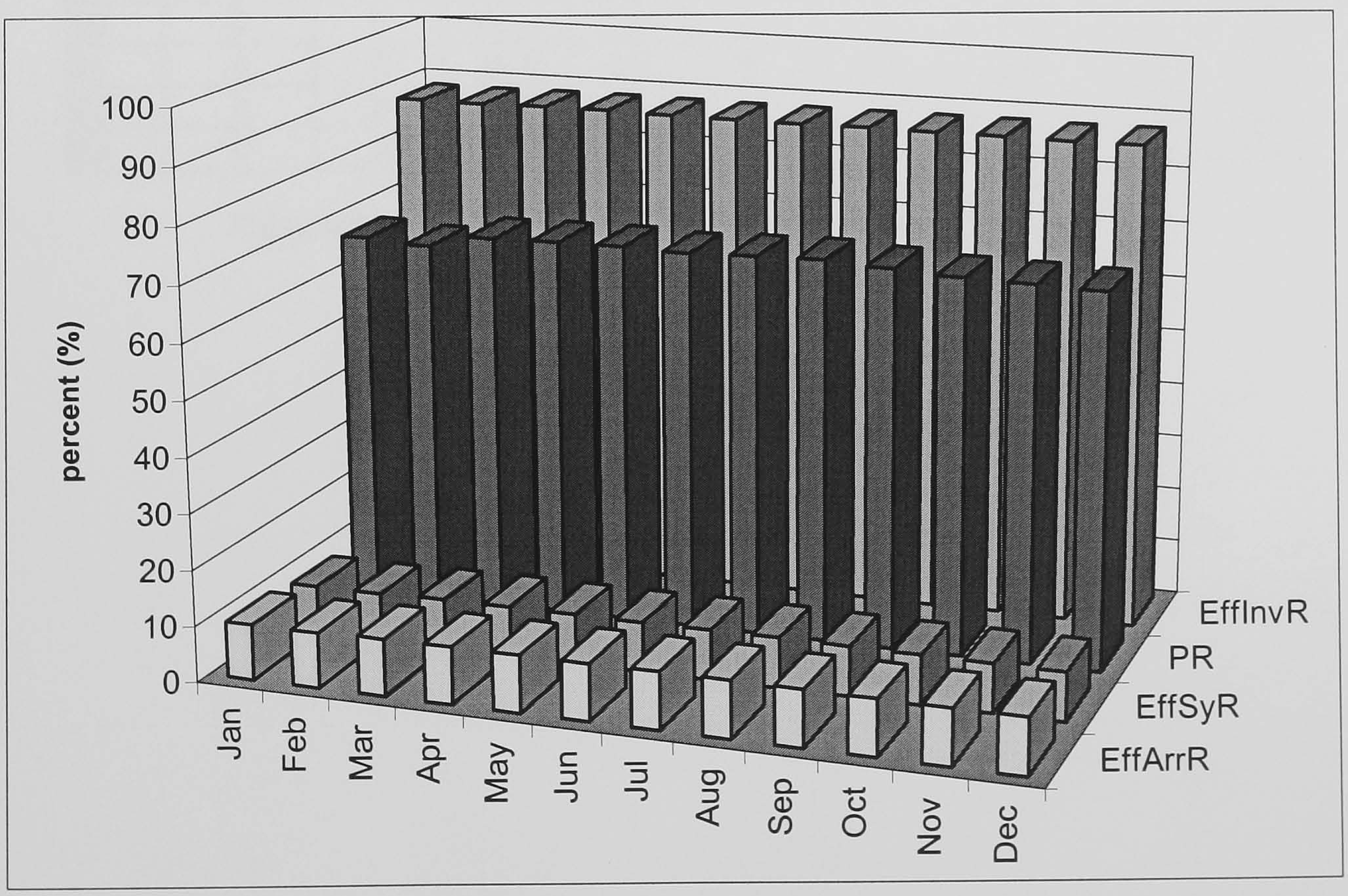


Figure 9.7: Graphical output of monthly system performance for Case 5PV.

The hourly average system performance p.a. for Case 5PV is shown in Table 9.6 and its graphical representations are shown in Figures 9.8, 9.9 and 9.10:

Hour	GlobHor (W/m²)	DiffHor (W/m²)	TArray (°C)	IArray (A)	UArray (V)	EOutInv (Wh)	EffArrR (%)	EffSyR (%)	PR (%)
0	0	0	25.5	0.0	0	0	0.0	0.0	0.0
1	0	0	25.1	0.0	0	0	0.0	0.0	0.0
2	0	0	24.7	0.0	0	0	0.0	0.0	0.0
3	0	0	24.4	0.0	0	0	0.0	0.0	0.0
4	0	0	24.1	0.0	0	0	0.0	0.0	0.0
5	0	0	23.7	0.0	0	0	0.0	0.0	0.0
6	64	45	25.7	1.3	87	91	7.2	4.6	35.7
7	227	135	31.2	3.8	92	299	9.7	7.8	60.3
8	393	209	36.9	6.5	93	528	10.3	9.0	68.9
9	542	257	42.7	9.1	91	733	10.4	9.2	70.6
10	651	291	47.8	11.1	90	872	10.4	9.1	70.4
11	710	311	51.5	12.1	88	939	10.2	9.0	69.5
12	689	307	52.8	11.7	87	898	10.1	8.9	68.4
13	648	293	53.2	10.8	87	828	9.9	8.8	67.4
14	534	253	50.7	8.9	88	684	9.9	8.7	66.7
15	395	202	46.6	6.6	88	503	9.7	8.3	64.1
16	220	132	41.0	3.6	88	272	8.8	7.1	54.6
17	66	45	35.7	1.2	88	87	5.0	3.5	27.2
18	0	0	31.3	0.0	0	0	0.0	0.0	0.0
19	0	0	29.5	0.0	0	0	0.0	0.0	0.0
20	0	0	28.0	0.0	0	0	0.0	0.0	0.0
21	0	0	26.8	0.0	0	0	0.0	0.0	0.0
22	0	0	25.9	0.0	0	0	0.0	0.0	0.0
23	0	0	25.2	0.0	0	0	0.0	0.0	0.0

Table 9.6: Simulated hourly system performance for Case 5PV.

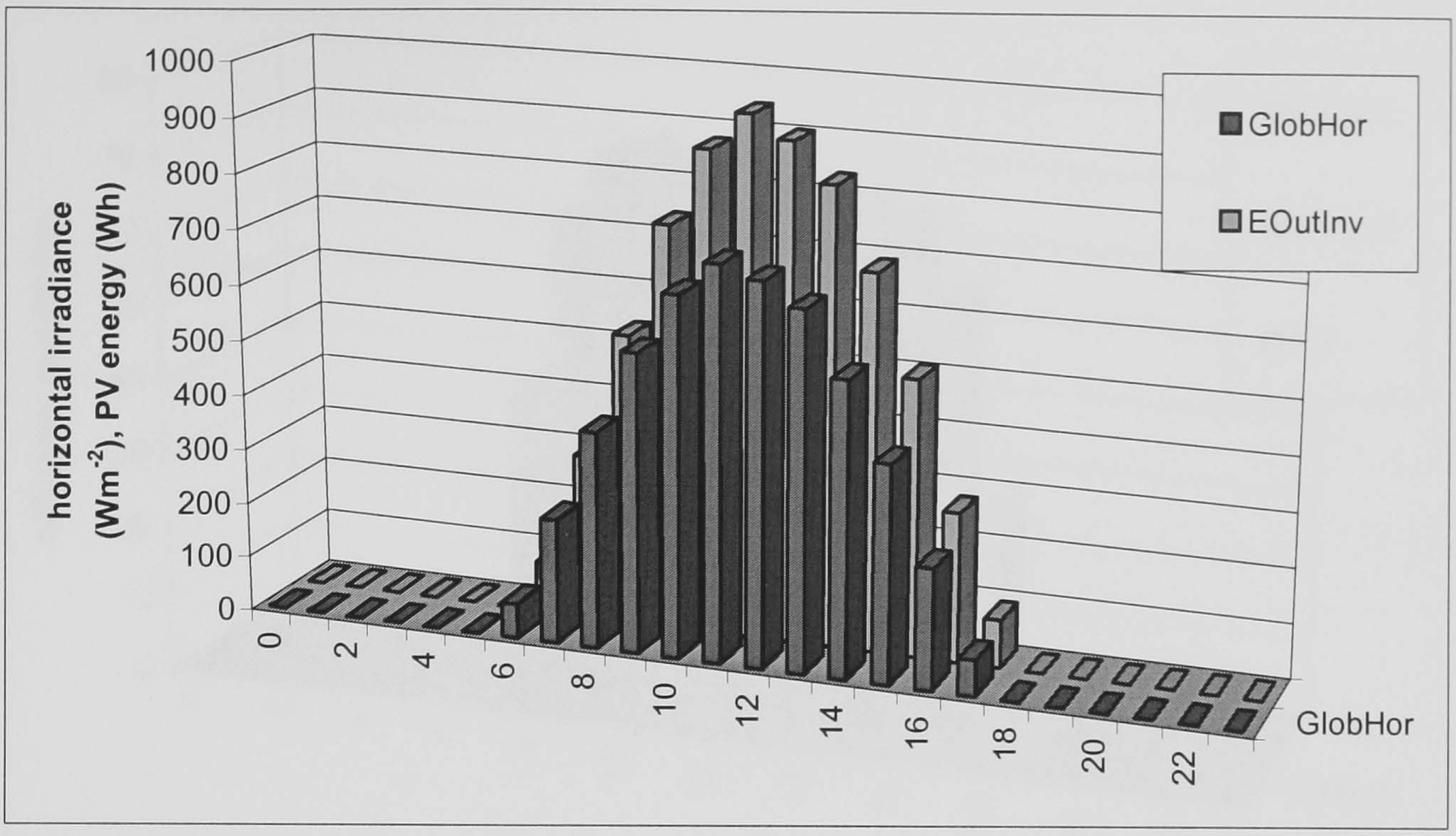


Figure 9.8: Graphical representation of simulated hourly system performance for Case 5PV.

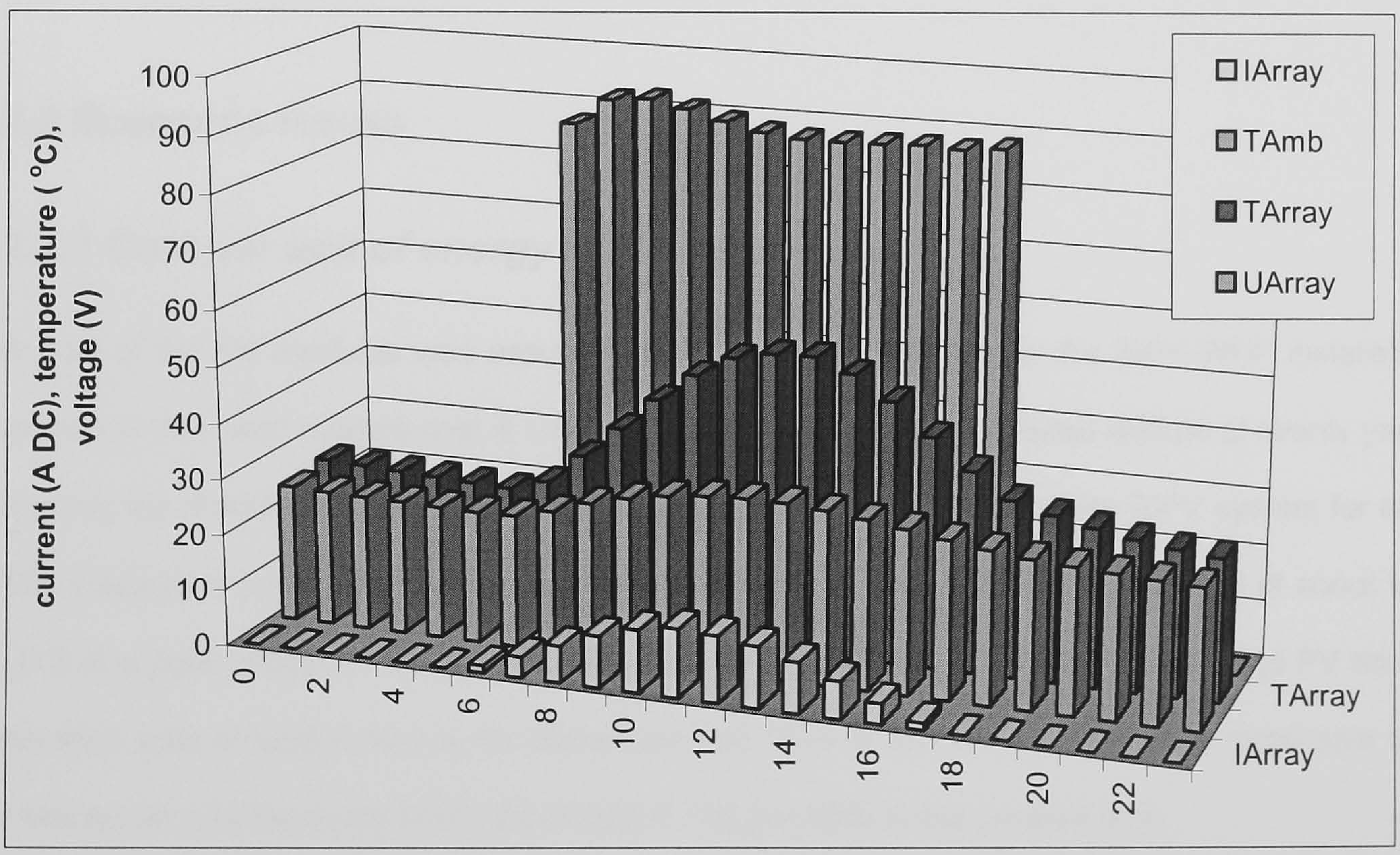


Figure 9.9: Simulated hourly system performance for BiPV-SMSB. IArray - array current, TAmb - ambient temperature; TArray - array temperature; UArray - array voltage.

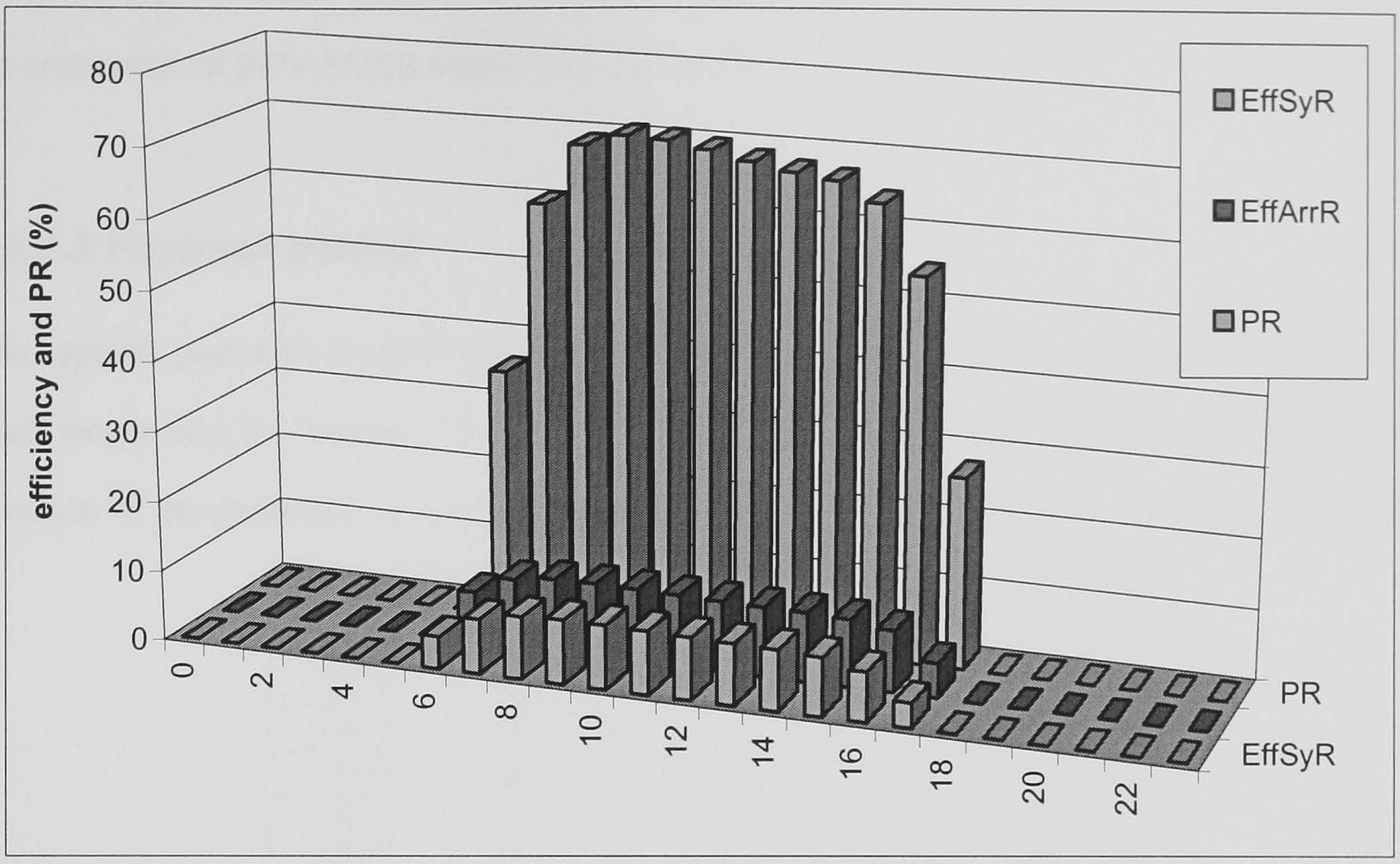


Figure 9.10: Simulated hourly system performance for BiPV-SMSB. EffSyR - system efficiency; EffArrR - array efficiency; PR - Performance Ratio.

9.2.4 Economic issues

9.2.4.1 Cost per unit of energy

The cost of the PV modules was assumed to be the same as that for the BiPV-WHF installation. This means that each module cost is US 6.18 per Wp and has an estimated lifetime of twenty years. Assuming the module cost to be 50 % of the total system cost, the complete BiPV system for each SMSB classroom application then costs US 12.36 per Wp, thus making the total cost at about US$ 24,473 at a peak rating of 1.9 kWp per classroom. These assumptions give an average PV energy generation cost of US$ 0.49 p.a. for Malaysian use. This is about 4.8 times more expensive than the Malaysian grid electricity tariff rate of US$ 0.102 per kWh at the present time.

However, when compared against other BiPV systems, this is about 43 % lower than the WHF generation and about 31 % lower than the UK average. It is also about 18 % lower than the average cost cited in other publications for the Northern climate latitudes of Europe and North America.

However, the Malaysian value is about double the Australian BiPV cost. Thus it can be seen that the application of BiPV-SMSB seems very promising.

9.2.4.2 Payback period

The payback period for the BiPV-SMSB system was calculated to be 48 years. This is still about 2.5 times longer than the lifetime of the PV modules themselves, using the present cost structures. The scenario for the projected costs and break-even points for the PV modules are shown in Table 9.7:

PV cost =	100%	90%	80%	70%	60%	50%	40%
100%	48	43	38	34	29	24	19
120%	40	36	32	28	24	20	16
140%	34	31	27	24	21	17	14
160%	30	27	24	21	18	15	12
180%	27	24	21	19	16	13	11
200%	24	22	19	17	14	12	10
220%	22	20	17	15	13	11	9
240%	20	18	16	14	12	10	8

Table 9.7: Payback period at break-even point for BiPV-SMSB application.

The break-even payback period of twenty years is within achievable limits if the:

- PV system costs drop to 40 % of its present costs
- Energy costs rise to 240 % of the present value.
- Any combination of either PV system drop in cost and energy cost hike.

9.2.5 Reference energy

The Malaysian average energy requirement for schools is much lower compared to the UK requirements. The respective values of energy demands are shown in Table 9.8:

Fuel type	UK Ave kWhm^{-2}	%	SMSB-1 kWhm^{-2}	%
Electricity	204.0	52.2	40.7	89.5
Fossil fuel	186.5	47.8	4.8	10.5
Total	390.5	100.0	45.5	100.0

Table 9.8: Average energy density for UK and Malaysian schools.

The graphical representation of Table 9.8 is shown in Figure 9.11:

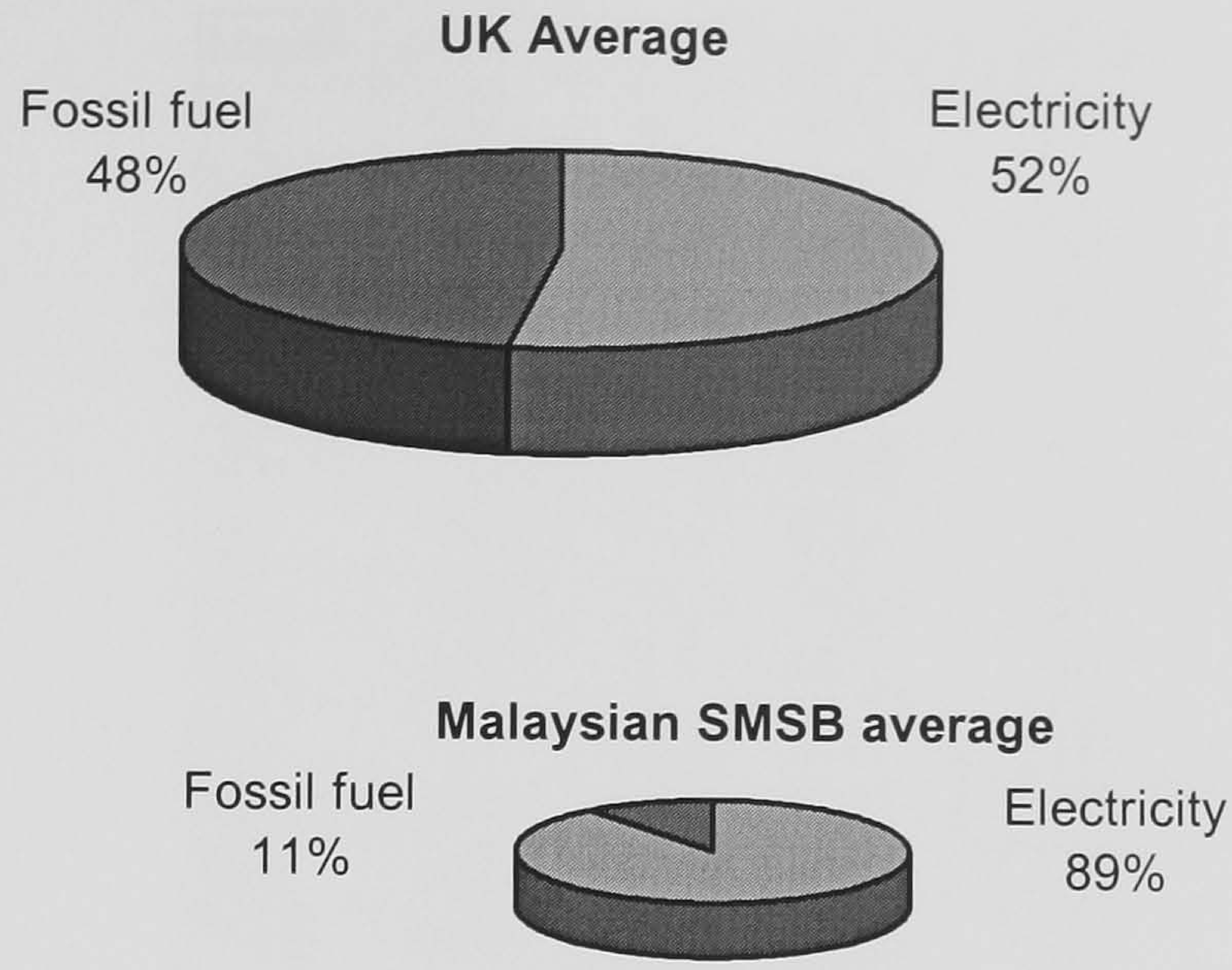


Figure 9.11: UK average school and Malaysian average SMSB energy density. The UK energy school demand is about eight times larger than the Malaysian school demand.

A detailed energy consumption of the SMSB by type is as shown in Figure 9.12:

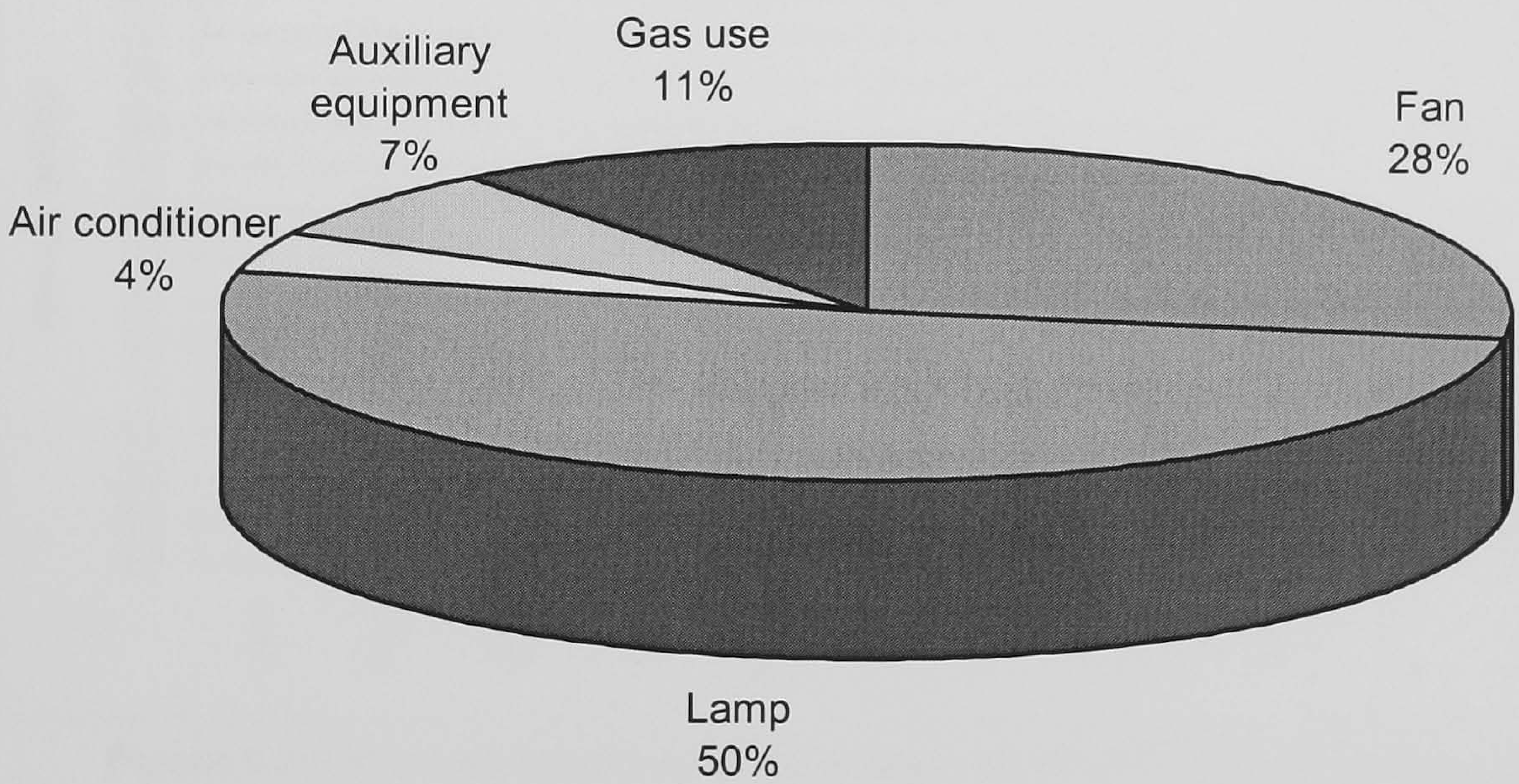


Figure 9.12: Detailed energy consumption by type for a typical SMSB.

The PV generation simulations in this research have been set-up to minimise the electrical energy consumption by the SMSB per classroom size. The approximate matching of the PV generation and energy demand for an SMSB is shown in Table 9.9 and in Figure 9.13:

Month	kWh-E	US$	kWh-PV	Δ(PV-E)
Jan	5854	526	6757	15
Feb	4549	409	6575	45
Mar	7101	638	7823	10
Apr	7010	630	7608	9
May	7782	700	7189	-8
Jun	7505	675	6646	-11
Jul	9860	886	6909	-30
Aug	10842	975	6922	-36
Sep	8706	783	6653	-24
Oct	9237	830	6646	-28
Nov	9237	830	5773	-37
Dec	2887	259	5856	103
Total	90570	8141	81357	-10

Table 9.9: Electrical energy demand (kWh-E) and PV generation (kWh-PV) for an SMSB. Δ(PV-E) - the percent difference between PV energy over existing energy demand.

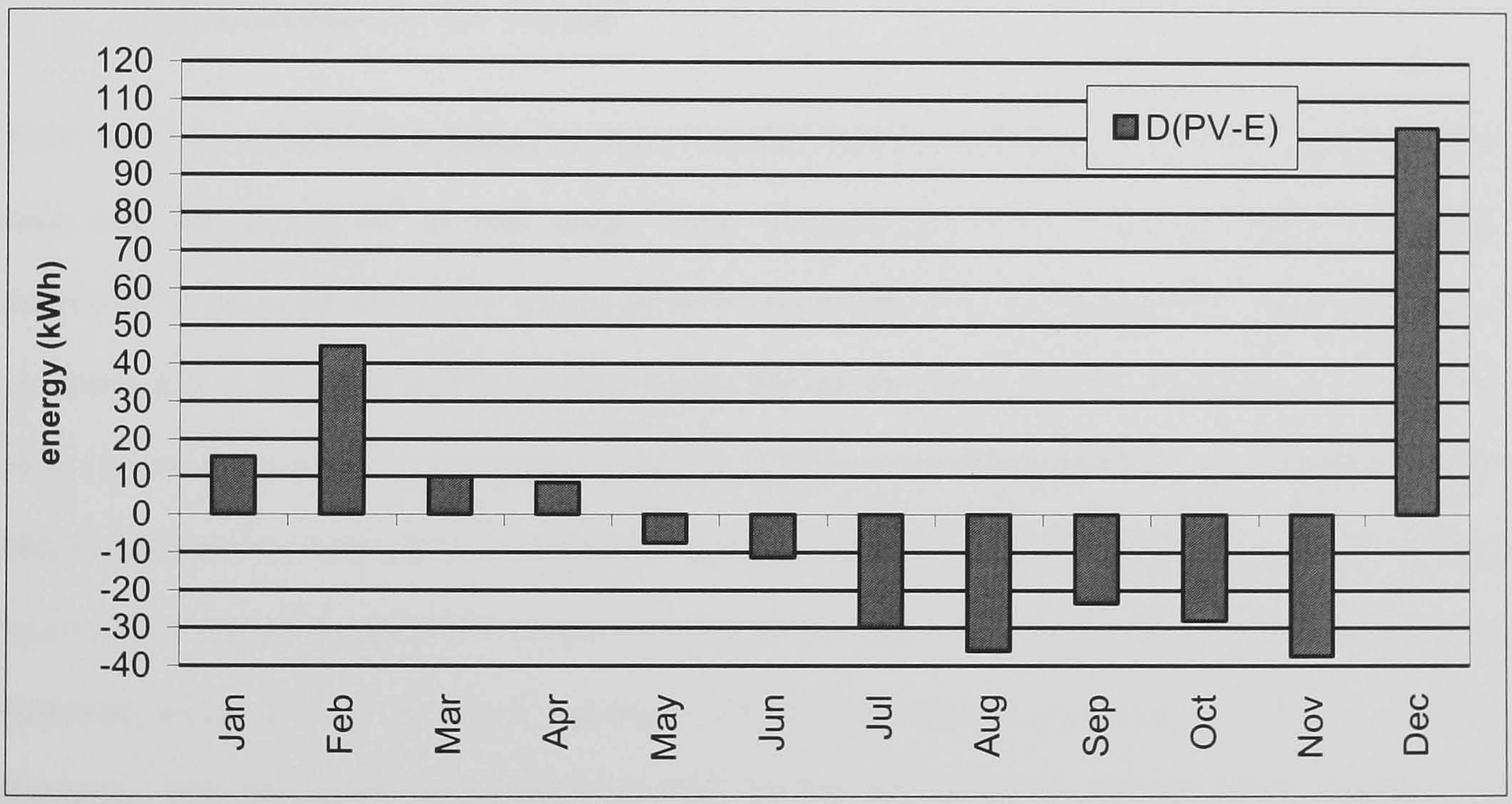


Figure 9.13: The load-matching of the energy requirement and PV energy generation.

From Table 9.9 and Figure 9.13, it can be seen that the PV energy generation nearly matches the energy requirement of the SMSB by a deficiency of about 10 % only. This difference is acceptable since the actual anticipated energy requirement of the SMSB is actually slightly lower than the value shown in Table 9.9. As a comparative example, the BiPV system performance at the WHF installation is presented against the SMSB simulated set-up shown in Figure 9.14:

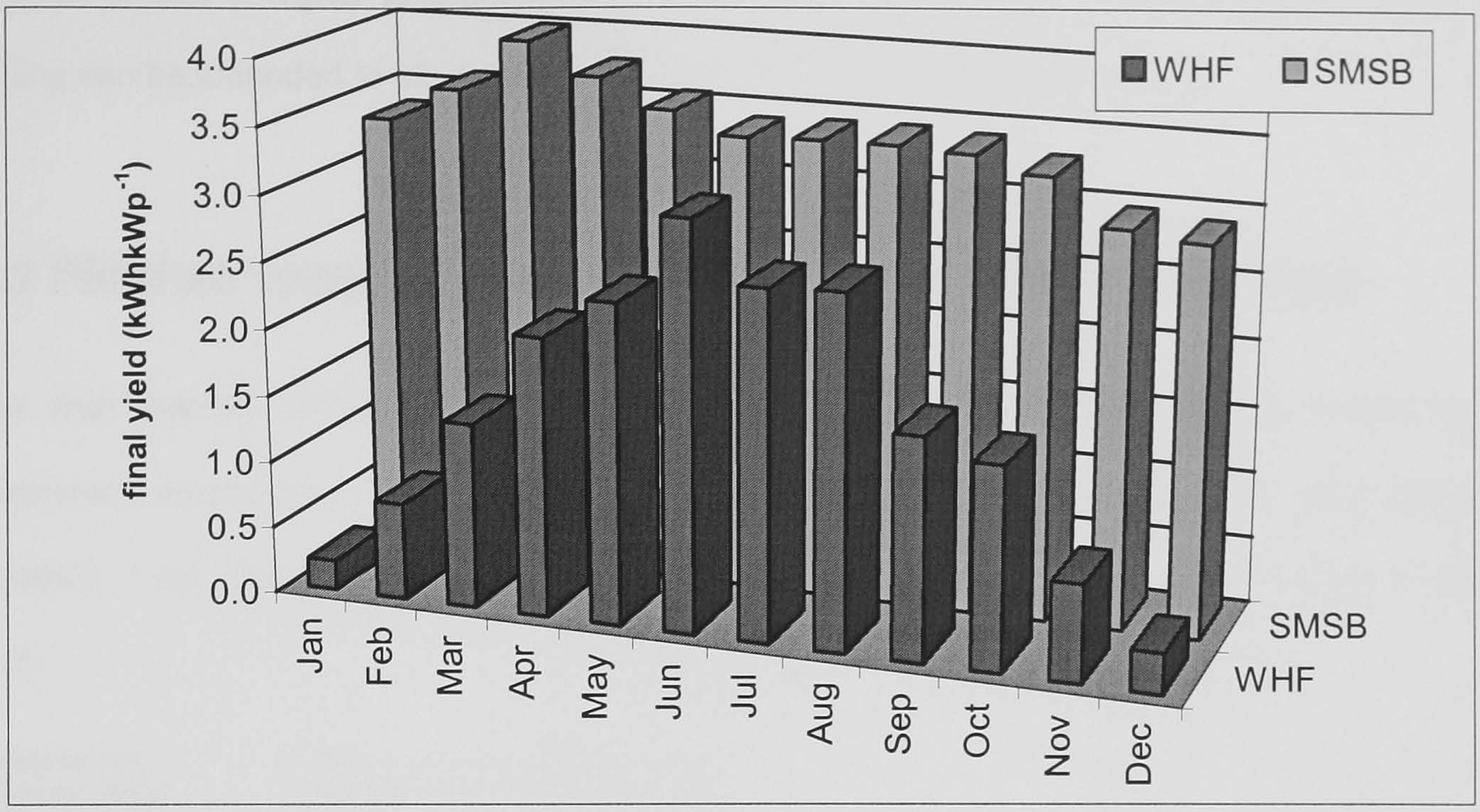


Figure 9.14: Final yield p.a. for BiPV-SMSB and BiPV-WHF systems. The pattern of BiPV generation for the SMSB design seems very stable throughout the year. This makes it an ideal application for the climate.

From the school statistics in Malaysia shown earlier, there are a total of 137,230 SMSB classrooms, each with about 118 m^2 of roof area. Thus, on average, if 13 % of all these roof areas per classroom is covered with BiPV arrays to minimise the 2,745 kWh energy requirement, there could be about 377 x 10^6 kWh of PV energy displacing conventional energy from the grid on an overall basis. In other words, an approximate demand of about 260 MWp could be met solely by the BiPV-SMSB applications from all the schools in Malaysia. With a peak demand of 5,730 MW using 1994 figures, this would make BiPV power contribute to about 4.5 % of the country's total capacity. However, even with 20 % of the maximum theoretical total of 260 MWp of BiPV installations in Malaysia, this becomes comparable in size to the programmes in the USA, several leading European countries and Japan.

In summary, BiPV applications for the SMSB design showed very promising and sensible results as obtained through the simulation work. The major parameter identified as having a role in the optimum system performance of the BiPV-SMSB application was relating to the operating temperatures of the PV arrays. With proper design considerations, this can be addressed and the adverse effects of higher temperatures on the PV performance can be controlled effectively. This finding can be extended to other generic building designs in Malaysia generally.

9.3 Final air temperature prediction in the SMSB classroom

The final thermal simulation execution set-up in SUNREL 1.0β was basically similar to the preliminary executions. Details of the SMSB architectural build-up and materials were input into SUNREL 1.0β. The final simulation set-up is best explained using the diagram shown in Figure 9.15:

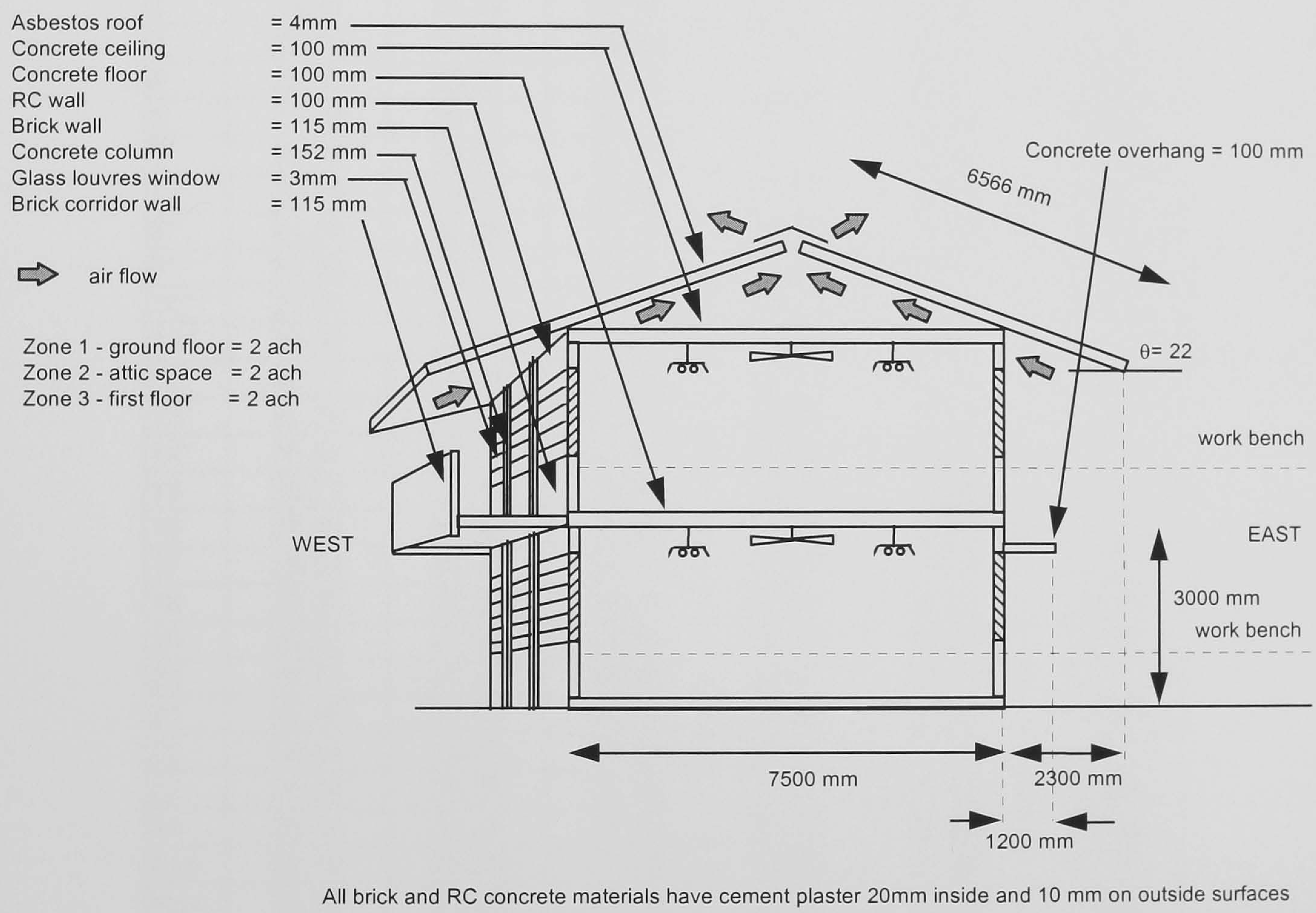


Figure 9.15: Final simulation set-up in SUNREL for SMSB.

The final simulation set-up in SUNREL 1.0β for the SMSB took the form of details from Case 1 as discussed in an earlier chapter. The attic floor was made of 100 mm concrete with 20 mm cement plaster on its upper surface and 10 mm cement plaster on its lower surface. The attic space was naturally ventilated with an air change rate of 2 ach^{-1} with the warmer air buoyed up and exhausted through the vents at the elevated ridge of the roof. This effect has been exploited by the BiPV simulations in Case 5PV as explained earlier.

9.4 Results, analysis and discussions

The simulated hourly temperature profile for the SMSB classroom for the original design in Case 0 and the final execution in Case 1 are shown in Table 9.10 and its graphical representation is shown in Figure 9.16:

Hr	C0 z1 ave	C0 z2 ave	C0 z3 ave	C1 z1 ave	C1 z2 ave	C1 z3 ave
1	25.96	25.97	26.98	25.92	26.54	27.54
2	25.81	25.74	26.75	25.79	26.32	27.50
3	25.66	25.52	26.53	25.66	26.12	27.18
4	25.52	25.31	26.32	25.52	25.93	27.00
5	25.38	25.15	26.13	25.40	25.76	26.83
6	25.24	25.01	25.95	25.27	25.62	26.66
7*	25.15	25.28	25.88	25.19	25.83	26.54
8*	25.20	26.86	26.19	25.26	27.12	26.56
9*	25.38	29.27	26.83	25.45	29.08	26.71
10*	25.60	31.74	27.59	25.68	31.10	26.93
11*	25.86	34.01	28.37	25.93	32.96	27.21
12*	26.11	35.34	29.02	26.17	34.11	27.52
13*	26.36	35.49	29.45	26.41	34.33	27.85
14*	26.61	34.77	29.67	26.62	33.77	28.18
15	26.79	33.18	29.63	26.78	32.54	28.43
16	26.89	31.45	29.42	26.86	31.18	28.60
17	26.94	30.10	29.18	26.88	30.09	28.69
18	26.90	28.88	28.87	26.84	29.07	28.68
19	26.81	27.93	28.53	26.76	28.28	28.59
20	26.71	27.46	28.26	26.65	27.87	28.47
21	26.58	27.08	28.00	26.53	27.56	28.32
22	26.44	26.78	27.74	26.40	27.29	28.15
23	26.29	26.50	27.49	26.27	27.04	27.98
24	26.14	26.24	27.25	26.13	26.82	27.80
Ave	26.10	28.79	27.75	26.10	28.85	27.66
Max	26.94	35.49	29.67	26.88	34.33	28.69
Min	25.15	25.01	25.88	25.19	25.62	26.54

Table 9.10: Temperature profile of original SMSB design and proposed design. C0 - Case 0 (original design); C1 - Case 1 (proposed design); z -zone. Values with * show the school hours. Zones 1 and 3 are the classrooms and zone 2 is the attic space.

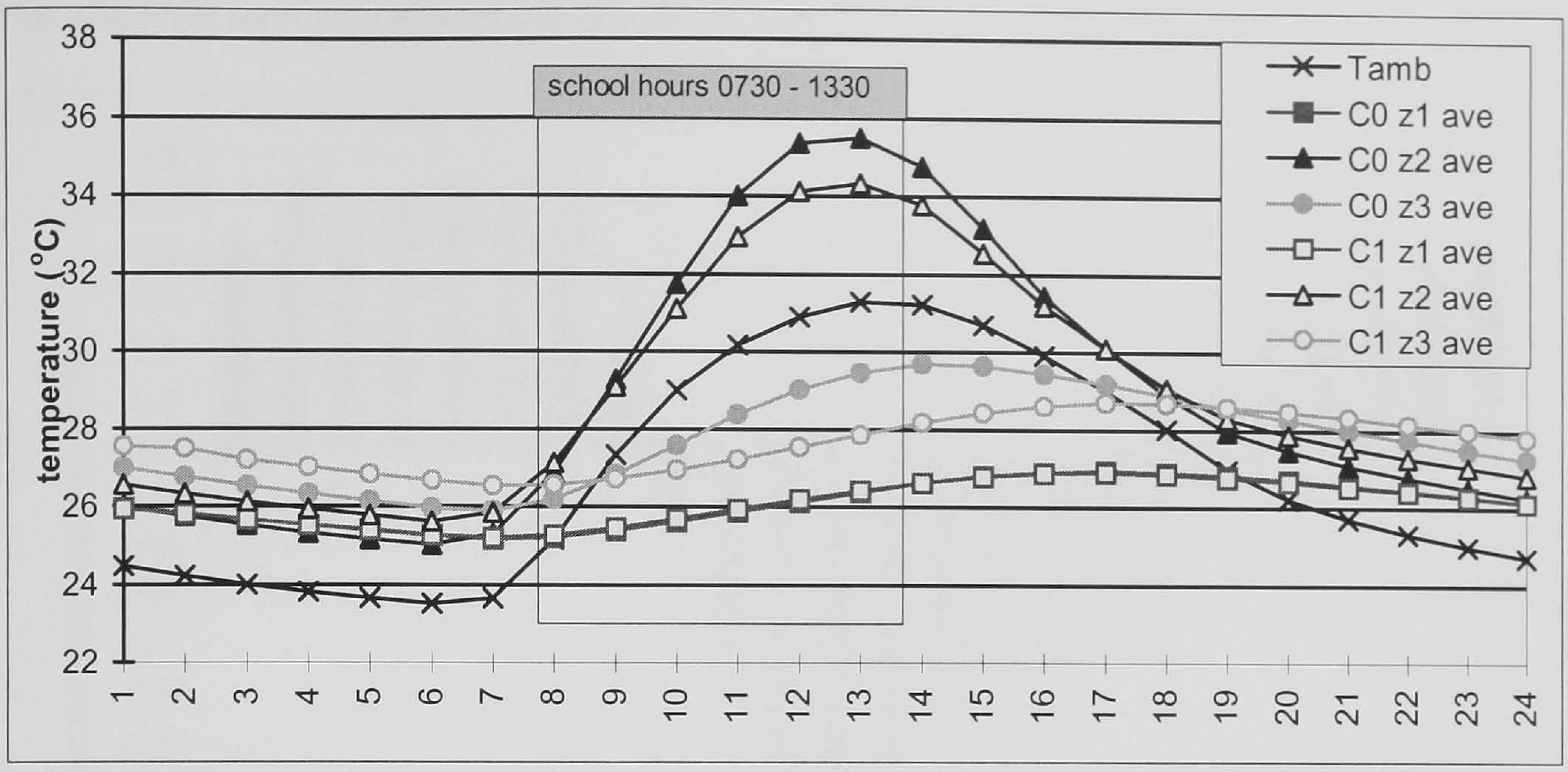


Figure 9.16: Overlay of temperature profile for Case 0 (C0) and Case 1 (C1). Tamb - ambient air temperature; z1 - zone 1 (ground floor); z2 - zone 2 (attic space); z3 - zone 3 (first floor).

An analysis of the temperature drop between Case 0 and Case 1 is shown in Table 9.11:

Hr	zone1 - ΔT	zone1 - (%) ΔT	zone2 - ΔT	zone2 - (%) ΔT	zone3 - ΔT	zone3 - (%) ΔT
1	-0.03	-0.12	0.57	2.16	0.56	2.06
2	-0.02	-0.07	0.59	2.25	0.74	2.74
3	0.00	-0.02	0.60	2.33	0.65	2.41
4	0.01	0.03	0.62	2.40	0.68	2.55
5	0.02	0.08	0.62	2.43	0.70	2.66
6	0.03	0.12	0.61	2.43	0.72	2.72
7*	0.04	0.17	0.55	2.14	0.66	2.51
8*	0.06	0.23	0.26	0.97	0.37	1.40
9*	0.07	0.28	-0.19	-0.65	-0.12	-0.45
10*	0.08	0.30	-0.64	-2.03	-0.66	-2.41
11*	0.07	0.29	-1.05	-3.14	-1.16	-4.18
12*	0.06	0.24	-1.23	-3.55	-1.50	-5.30
13*	0.05	0.17	-1.17	-3.34	-1.60	-5.57
14*	0.01	0.04	-0.99	-2.90	-1.49	-5.16
15	-0.01	-0.05	-0.64	-1.95	-1.19	-4.12
16	-0.03	-0.12	-0.27	-0.87	-0.82	-2.82
17	-0.05	-0.19	-0.01	-0.04	-0.49	-1.68
18	-0.06	-0.21	0.19	0.65	-0.19	-0.66
19	-0.06	-0.22	0.34	1.22	0.06	0.20
20	-0.05	-0.20	0.42	1.51	0.21	0.75
21	-0.05	-0.18	0.48	1.74	0.33	1.16
22	-0.04	-0.15	0.51	1.90	0.41	1.48
23	-0.03	-0.10	0.54	2.03	0.49	1.75
24	-0.01	-0.05	0.57	2.16	0.55	1.98

Table 9.11: Temperature differences between original SMSB design in Case 0 against proposed design in Case 1. Negative indicates drop in temperature. School hours are shown with *.

The graphical representation of the values in Table 9.11 are shown in Figure 9.17:

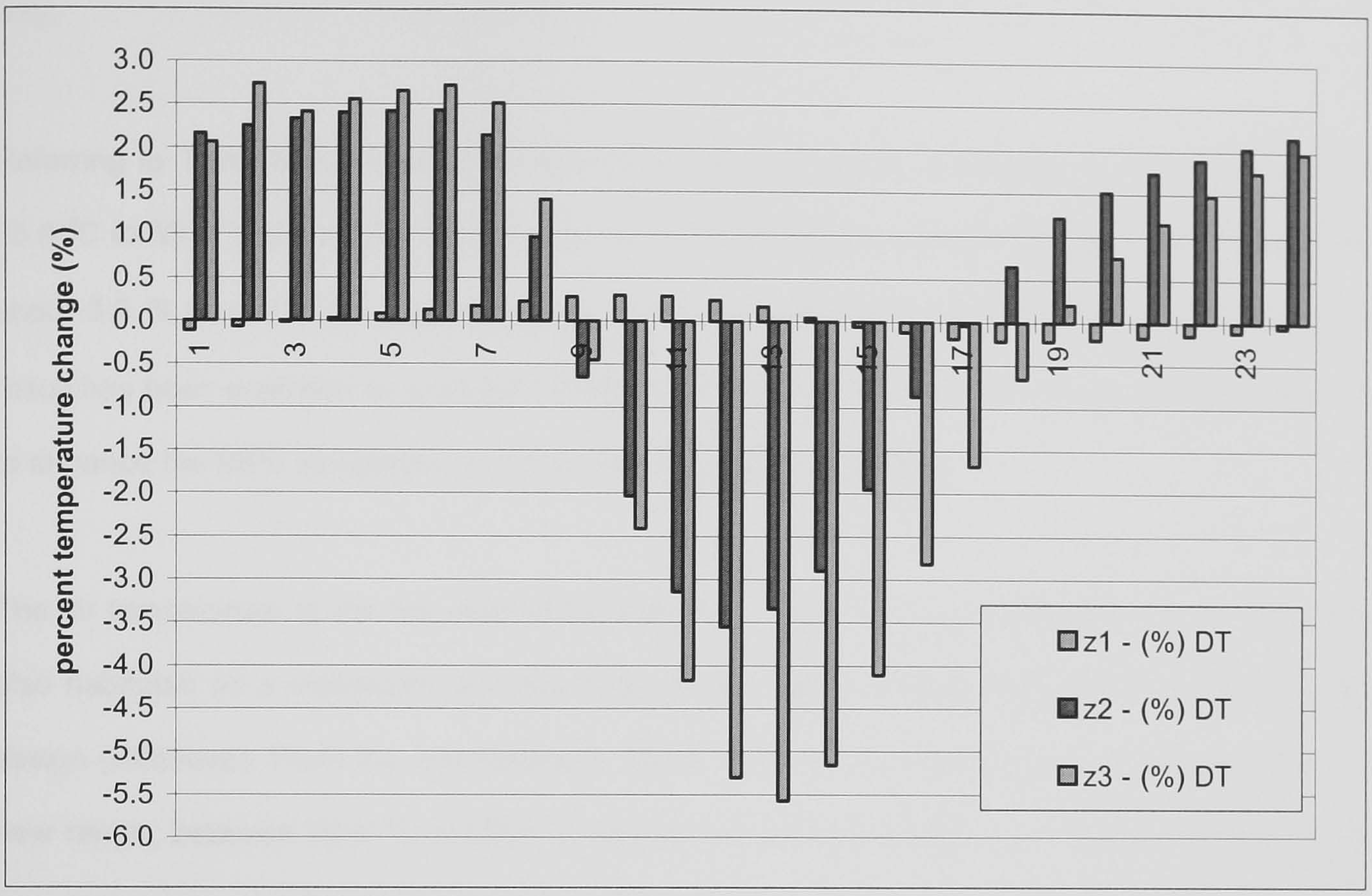


Figure 9.17: Differences in air temperature for the original SMSB classroom design and the proposed design. DT - change in air temperature. Negative indicates temperature drop.

As mentioned in an earlier Chapter, the measured comfort air temperature for Malaysians was 28.2 °C. From the final simulation results of Case 1 (C1z1ave and C1z3ave) as shown in Table 9.10, it can be seen that this is very near the target comfort air temperature. This is shown by the simulated overall SMSB classroom air temperature during the school hours for the habitated classrooms in zone 1 and zone 3, which ranged from 25.2 to 28.2 °C. Air temperatures in these zones give an average of 26.9 °C over 24 hours for the habitated classrooms. This average is the same as in the original design in Case 0 which ranged from 25.2 to 29.7 °C with a daily average of 26.9 °C.

The air temperature in the ground floor (C1z1ave) did not change very much and practically maintained the existing range (C0z1ave) from 25.2 °C to 26.6 °C during the school hours as anticipated. This is due to the rather heavy thermal mass of the whole building coupled with the fact that this classroom is naturally ventilated. Since the attic air space is rather "far away" from this floor, any relatively smaller effects from the changes in the attic space is not "felt" in a significant way.

Referring to Table 9.10, the air temperature in the attic space (C1z2ave) in Case 1 ranged from 25.8 °C to 33.8 °C during the school session. This represents a drop in the peak air temperature of about 3.6 % from Case 0 (C0z2ave) as shown in Table 9.11 (zone2-%ΔT) at 1200 hours. This result has been exploited to optimise the system performance on the PV arrays and has been used to enhance the BiPV simulations in Case 5PV as described earlier.

The air temperature in the first floor (C1z3ave) from Table 9.10 is of special interest. This floor is also habitated as a classroom and has been giving higher temperatures from the original SMSB design (C0z3ave). From the simulations in Case 1, the air temperature dropped considerably to a new range, between 26.5 °C to 28.2 °C during the school session. It is observed that the peak temperature at school's end dropped by a peak difference of about 5.6 % from the original design in Case 0 as shown in Table 9.11 (zone3-%ΔT) at 1300 hours. This temperature drop is one of the main targets that was emphasised during these simulations, as the aim was to bring the air temperature of this floor as close as possible to the target of 28.2 °C. Thus, as shown from these results, Case 1 seems to be the optimum option for the BiPV-SMSB design as a whole. The graphical representation of these results are shown in Figure 9.17.

In summary, the air temperature in the SMSB classrooms can be lowered to within the comfort air temperature for a naturally ventilated classroom in Malaysia, using the proposed design of Case 1.

Chapter 10. Conclusions, Guidelines and Recommendations

10.1 Conclusions and recommendations for the BiPV-WHF site

From the results and analysis of the findings from the BiPV-WHF installation, it can be concluded that the system gave an overall performance that resides on the lower end of the normal operating spectrum. This is seen with a final yield of 498 $kWhkWp^{-1}$, an array yield of 1.4 $kWhd^{-1}kWp^{-1}$ and a PR of 53 %. Consequently, the economic cost of the system is on the higher end with an installed cost of US$ 19.47 per Wp, a generation cost of US$ 1.24 and a payback period of 97 years. However, this is considered as comparable with other practical installations such as the Northumbria building or the German programme.

Issues regarding the BiPV-WHF installation relate to inherent architectural design limitations, inverter faults, non-optimum orientation of the modules, excessive heating of the modules and inverter mismatch problems. The architectural design of the building has given rise to shading of the modules for many positions of the sun in the sky. The original EPROM setting within the inverter that caused inumerable trippings largely lowered the PV energy yields. The non-optimum orientation of the modules hindered maximum performance. The excessive heating of the modules due to lack of ventilation and heating regimes in the cooler months have altered the performance of the PV system. The inverter over-size with respect to the PV modules lowered efficiency of the system. These issues had plagued the BiPV-WHF system and had caused the system to be operating at the lower end of the spectrum.

Recommended measures to improve the performance of the system include, permutational wiring of the existing system to match the architectural design of the building and matching of the inverter-PV sizes. An alternate solution would be to place the PV modules on the highest roof of the building, with proper considerations in architectural and engineering aspects to minimize problems explained earlier.

10.2 Conclusions and recommendations for PVSYST 2.0 model

From the results and analysis of the comparative analysis using PVSYST 2.0 on the measured values from BiPV-WHF system, it was found that the computer model performed simulations that were encouraging, despite the inherent design and operating difficulties of the site. In summary, PVSYST 2.0 over-predicted the AC output by an average of about 15 %, mostly over-predicted the hourly DC array output from -0.3 to 19.5 % and under-predicted the hourly array temperature from a -8.5 to 0.3 ^{o}C. The default setting within PVSYST 2.0 using an uncovered back panel had affected its predicting capabilities for the BiPV-WHF system, which actually had the back of its PV panels covered. Coupled with the heating regimes during the cooler months, the algorithm without a proper thermal engine, predicted results that differred from the measured values for the site.

Recommended enhancements of the model's capabilities include coupling with a commercial CAD software and a building thermal engine. Further work in improving the model's irradiation algorithm is suggested, to increase its accuracy in relation to predicting performances of BiPV systems.

10.3 Conclusions for BiPV-SMSB simulations

From the results, analysis and discussions presented on the Malaysian BiPV simulations, several conclusions can be drawn with regards to the use of BiPV technology for the SMSB application. The application of BiPV technology in the SMSB design through simulation using PVSYST 2.0 showed that:

1. The application of BiPV technology in SMSB design is only suitable and sensible if the PV arrays are integrated on the rooftops. The integration of the PV arrays as awning or sunshade devices above window frames, commonly practised in BiPV installations in Northern latitude climates

should not be imitated for Malaysian applications. This is simply because of the geographical location of Malaysia on the globe and the basic architectural SMSB design that will cast partial or complete shadows on the PV arrays if integrated as an awning device. This not only lowers the system performance, but also deteriorates the solar cells themselves.

2. BiPV technology is well suited for rooftops of the Standard Malaysian School Building design. The existing architectural design offers minimal shading losses to the BiPV arrays. The only shading comes from the fact that the PV arrays are inclined at 22° from the horizontal and that the PV arrays are integrated on the East-facing and West-facing roofs of the SMSB. Since the geographical location of the country is very near the Equator, there appears to be no other choice of integrating the panels onto the SMSB roof design, thereby giving rise to the sun rising from the back of both BiPV arrays in certain limited times of the day. The only real concern is with regards to the elevated cell temperatures which may peak up to 20 to 40 °C above the peak ambient temperature. This parameter directly influences the system performance of the BiPV application in the SMSB design specifically, and in other applications in the Malaysian built environment generally. However, this can be controlled by ventilating the BiPV arrays, at least naturally, by simple but proper architectural designs as shown in the final results of the simulations.

3. The system performance of BiPV-SMSB applications yielded excellent results when the modules were integrated on the roof with a final yield of 1,245 $kWhkWp^{-1}$ p.a., an array yield of about 3.4 $kWhd^{-1}kWp^{-1}$, an array conversion efficiency of 10 %, a system efficiency of 9 % and a PR of 68 % p.a. This is considered as excellent compared to most other Northern climate latitudes applications, except Australia. These values can be used as a reference for other prospective BiPV applications in Malaysia.

4. The costs of the technology and energy generation are still the main issues in its proliferated use. This is in spite of the higher performances of the BiPV-SMSB exploratory simulations done in this research project. The simulated Malaysian BiPV applications gave a better PV energy

cost at US$ 0.49 per kWh compared to most published literature and a better payback period at 48 years as compared to applications in Northern climate latitudes.

5. The application of BiPV technology in SMSB design seems to be very promising due to the large numbers of available rooftops of existing schools. In addition, the energy requirement of the SMSB at 2,745 kWh per classroom p.a. is well within the generating capacity of the BiPV arrays, which needs only about 13 % of the total existing roof area to practically displace it. This can be achieved by designing the SMSB per classroom with 1.9 kWp of PV capacity. Estimated projections revealed that the BiPV-SMSB applications could provide up to 260 MWp of PV power for the whole country, i.e. about 4.5 % of the peak demand. This projection could also be contemplated for other rooftops in the residential and commercial sectors.

6. Relevant issues regarding the application of BiPV technology in Malaysia would include exposure and training for suitable construction builders, electrical and mechanical contractors to ensure sound integration.

7. The air temperature in the existing SMSB design classroom could be made closer to the comfort air temperature level of 28.2 °C by having minimal architectural design changes. This was shown to be achievable by creating air movements in the attic space, the least of which is through natural ventilation. The optimum air change rate as simulated in this research project was 20 ach^{-1}. However, by ventilating it naturally for a worst case scenario, with an air change rate of 2 ach^{-1}, the target air temperature appeared to be achievable with a different alternative of ceiling materials. To achieve this, the existing 4 mm asbestos sheet as ceiling material for the two-level SMSB classroom design would be replaced by a 100 mm concrete slab coupled with an air change rate of 2 ach^{-1}. This combination of air change rate and concrete ceiling material was shown to be able to lower the air temperature of the SMSB classroom in the existing design to meet the targeted internal air temperature.

10.4.General guidelines for BiPV application in SMSB design

This section outlines a summary of the general methodological guideline for BiPV applications in the Malaysian built environment the design stage. It can be used as a quick reference that describes a methodology that may be used when exploring BiPV technology application in other SMSB designs specifically, and the built environment in Malaysia, generally. The outline is best described using Figure 10.1:

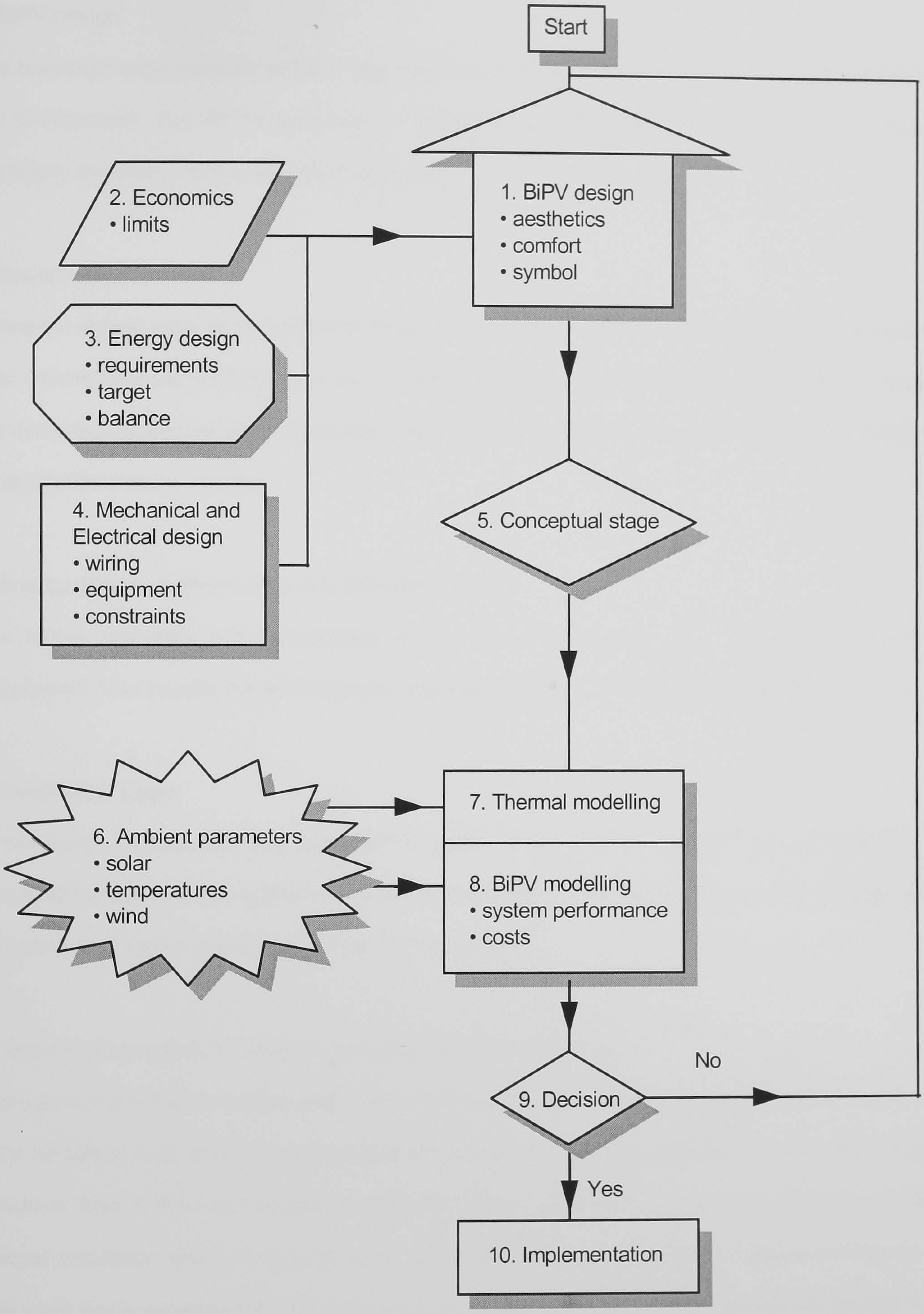


Table 10.1: General methodological guideline for BiPV applications in the Malaysian built environment.

1. BiPV design

The building design includes existing requirements such as protection from discomfort coming from the environment. For BiPV applications in Malaysia, the synergistic advantages include aspects relating to aesthetics and a symbol of statement.

2. Economics

Economic issues such as budget constraints are to be considered for Malaysian BiPV applications. This means financial implications from the BiPV technology and energy requirements. An issue of the economic reason for BiPV application should be contemplated as it often dictates the extend of its applications to the building.

3. Energy design, 4. Mechanical and Electrical designs

The sizing, matching and compatibility issues of grid-connected BiPV applications are to be considered. This engulfs the technical and engineering issues relating to BiPV technology.

5. Conceptual stage

At this point, a conceptual idea of the BiPV system of the built-form should have crystallised. The conceptual ideas can be translated into dimensional forms and contemplated upon. A scale model may be built to assist appreciation of the BiPV built-form.

6. Ambient parameters, 7. Thermal modelling, 8. BiPV modelling

This part is the actual simulation part. The ambient parameter serves as input into a comprehensive BiPV modelling tool, which may comprise of thermal and shading algorithm engines for the BiPV built-form. Should this not be available, then, the ambient parameter is input into a separate building thermal simulation model to predict array temperatures of the PV panels. These predictions are then input into a separate BiPV simulation model so as to enhance its PV generation engine. From this stage, results of the system performance, frequently given as global and hourly values are generated.

9. Decision

Based on results from the preceding stage, a decision with regards to the acceptability of the BiPV installation is made. The whole iteration process may be repeated for other permutational options or choices.

10. Implementation

This is the implementation stage of the process.

The system design from the BiPV-SMSB application is expected to perform favourably from a solar irradiation of 5 $kWhm^{-2}d^{-1}$. This may also apply to other similar rooftop BiPV applications in Malaysia generally. The system performance is expected to have a yield between 1200 to 1300 $kWhkWp^{-1}$ p.a., an array yield of at least 3 $kWhd^{-1}kWp^{-1}$ and a PR of about 70 %. The array and system efficiencies are expected to be around 10 % and 9 % respectively, while the inverter efficiency is expected to be around 90 %. These anticipated basic generic system performances for BiPV applications in the Malaysian built environment are graphically represented in Figures 10.2, 10.3 and 10.4:

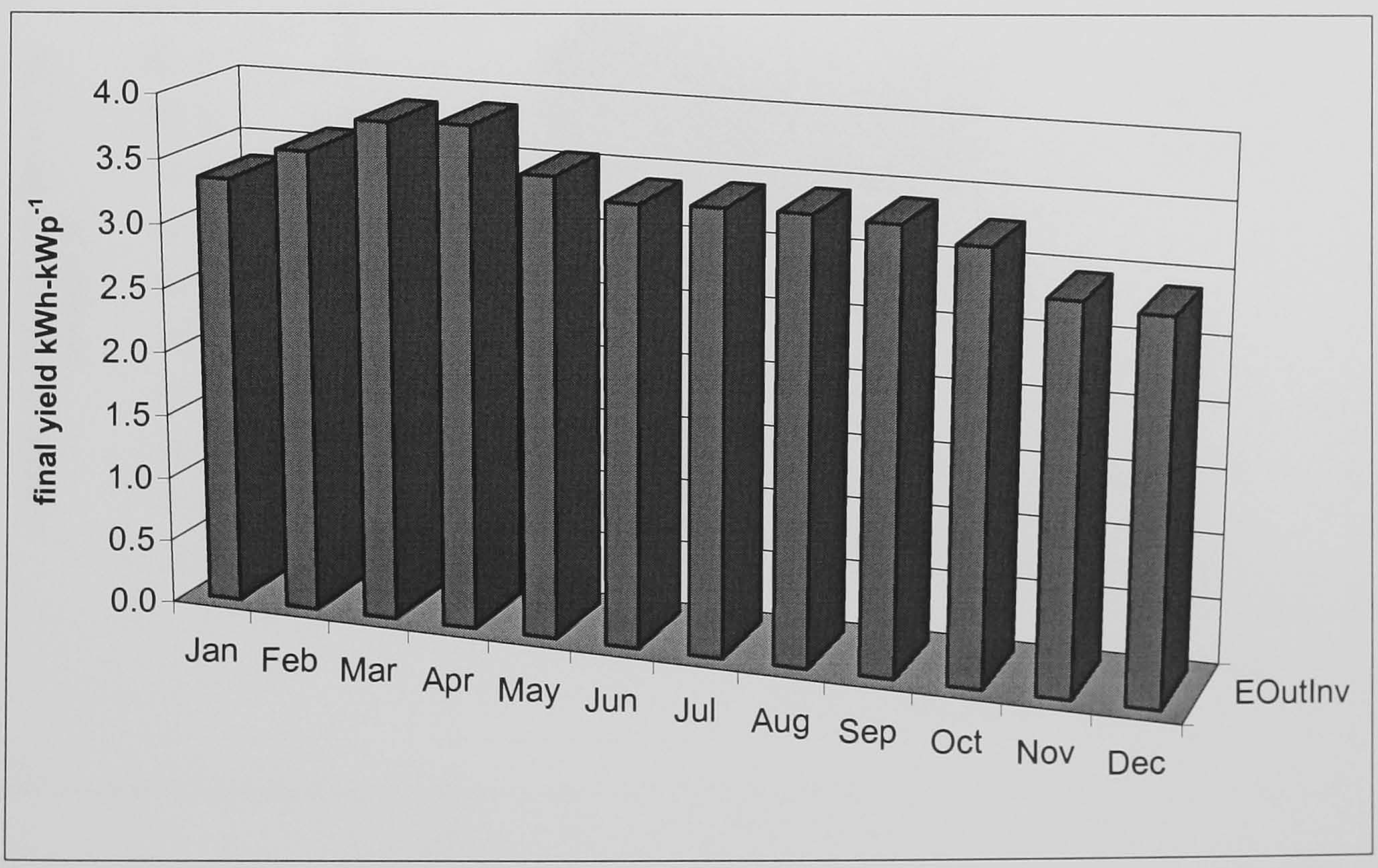


Figure 10.2: Monthly system performances. EOutInv - final energy output after the inverter.

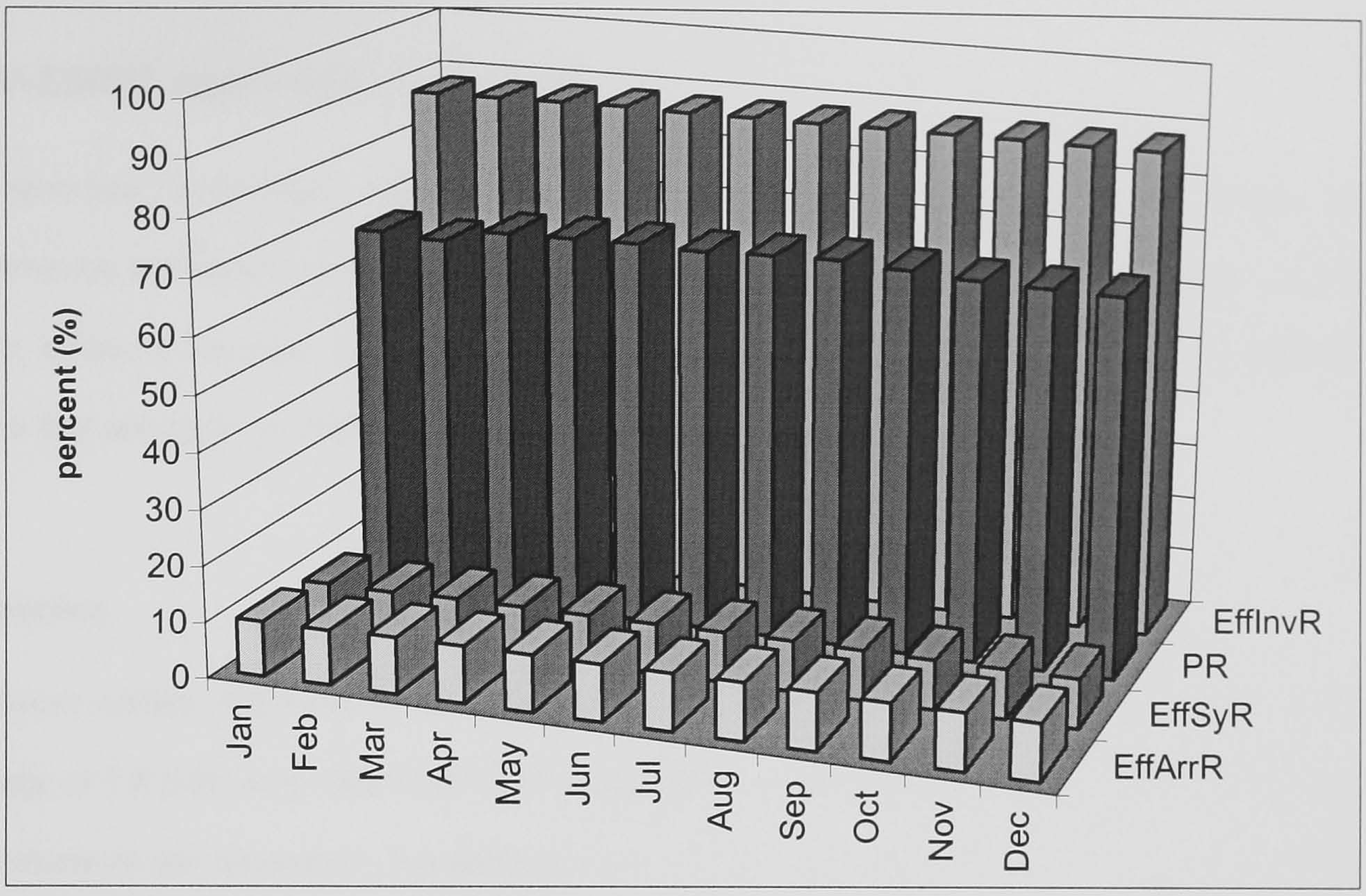


Figure 10.3: Monthly efficiency values. EffArrR - efficiency of array; EffSyR - efficiency of system; PR - Performance Ratio; EffInvR - efficiency of inverter.

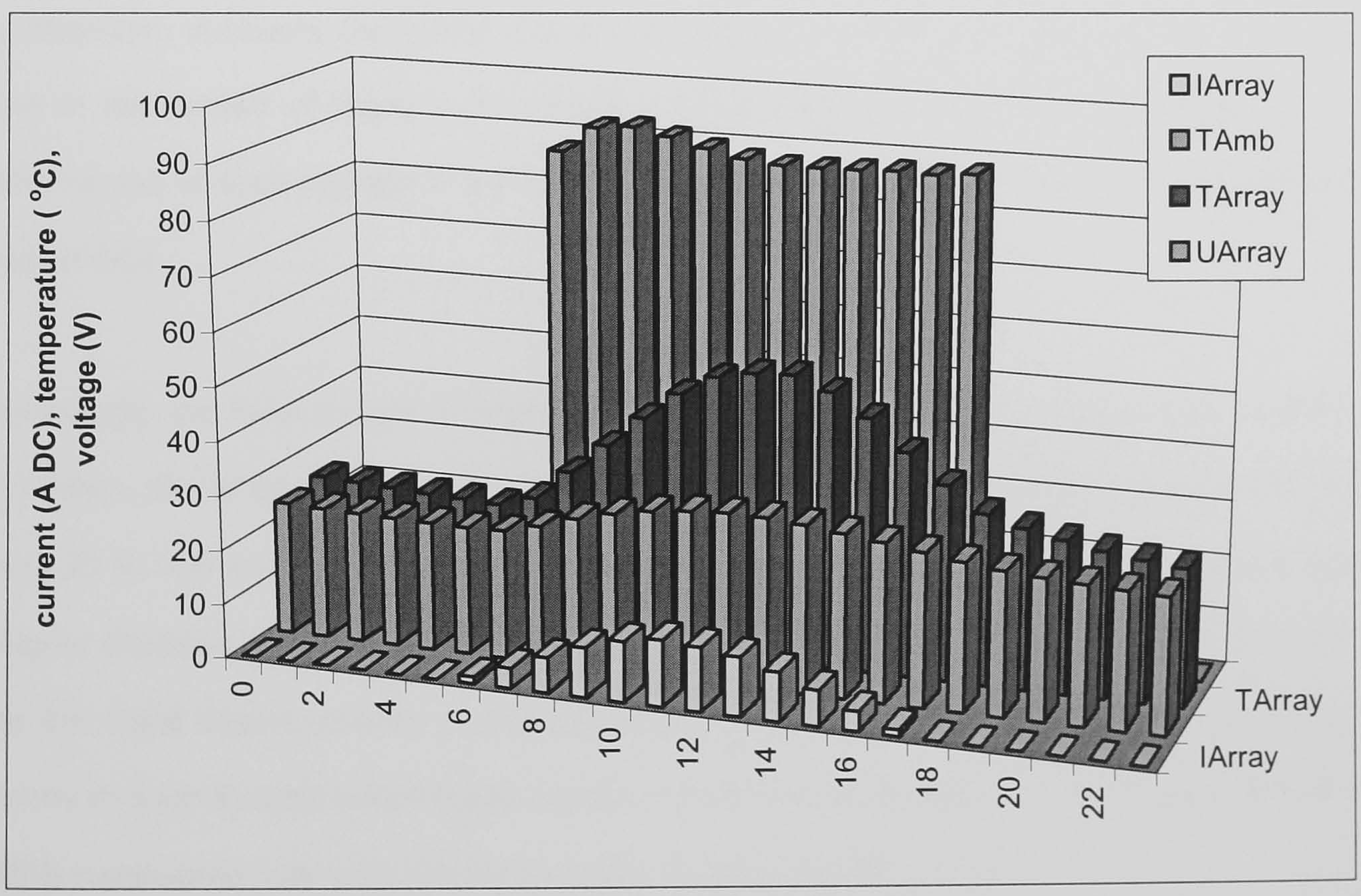


Figure 10.4: Hourly DC array outputs. IArray - array current; TAmb; TArray - array temperature; UArray - array voltage.

BiPV-SMSB application in perspective

The technical exploratory simulations of the BiPV-SMSB applications have shown that its performance in Malaysia is higher than most applications in Northern latitude countries, such as the UK. In addition, the cost of generation is also much cheaper. However, there are several other factors that are seen as having underlying influence to its widespread use.

Economics

As shown earlier, the cost for a complete working BiPV-SMSB classroom system with a peak capacity of 1.9 kWp was US$ 24,473 with a generation cost of US$ 0.49 per kWh. With an average of 34 students per classroom, the BiPV cost per student ratio becomes US$ 719.79 per student p.a. The 1994 GDP p.a. was at US$ 3,708 per capita and the 1994 energy expenditure was 1,500 kWh per capita. Thus the BiPV cost per student takes up about 19.4 % of the GDP. In essence this seems “quite high” as viewed in the perspective of a developing nation, where other issues such as development, economic prosperity and security often rank high in the nation’s list of priorities. As seen in the context of being a developing country which is a “net energy producer”, the cost-effectiveness of such projects in the urban areas already powered by thermal power plants seems questionable.

Interestingly, the fiscal budget for Malaysia in 1998 (Malaysian Budget 1998) totalled at about US$ 26.7 billion. Out of this, the allocation for R&D was a low 0.4 % and the spending for education was about 20 %. It is worthwhile to mention that Malaysia has been having one of the highest spending budgets allocated for education for a long time amongst the developing nations in the world, and that this trend seems unlikely to change much. Coupled with a target in powering much of the country through its rural electrification programme, it seems plausible that the funding of such BiPV-SMSB installations may very well be sourced from the education sector.

Energy programme expenditure

In the Seventh Malaysia plan (1995 to 2000), the allocated expenditure for energy programmes relating to electricity amounts to US$ 10.95 billion. The bulk of the spending has been allocated to thermal power plants, with about 39 % of the share. The spending share for rural electrification programmes amounts to about 2 %. However, interestingly, the transmission and distribution of electrical power has been given about 57 % share of the total allocation. Thus it seems that having considerable numbers of BiPV installations throughout the country, especially in rural communities makes economic sense. Besides having synchronised PV power in the daytime, traditional transmission and distribution losses, and certainly costs, can be minimised by having the PV generators integrated in the buildings, especially for the rural communities and institutions. This benefit can be realised immediately as a direct consequence of BiPV technology implementation.

Environment

The Seventh Malaysia Plan has expressed acceptance and concerns of environmental issues as a factor in energy planning and policy. The government has targeted hydro technology as a complementary source of power. Quite recently, the use of electric-based urban public transport has been introduced in tandem with calls for zero-emission public transport within the international community. Within Malaysia, despite having PV technology established and expanding in the isolated power systems, such parallelism in the urban and built environment is yet to be heard of and seen in existence. However, with the anticipated increased use of electric-based urban public transport, BiPV use is likely to be introduced as an indirect consequence, in the not too distant future.

Socio-political factors

As Malaysia is a democratic country, the fate of the nation is theoretically dependent upon her citizens. Since independence from the UK in 1957, the government in Malaysia has been steered by basically the same coalition party which has proved to be very stable, compared to other nations of similar histories. Factors for such a state can be attributed to internal and external factors.

Internally, as the population becomes better educated, there tends to be a general trend to have an increased awareness amongst the citizens towards many changes; amongst which climate change as a relevant issue in this research project. This trend seems to be sustainable with the amount of government spending in education. In addition, economic affluence, which is always in harmony with better education, tends to increase the ability of citizens to make choices. These factors make ripe a situation for the eventual acceptance and widespread application of BiPV technology.

As the country spirals towards regional and world significance in terms of prosperity, global economic, political and sociological influences are expected to transcend geographical boundaries. Thus international energy and climate agendas will need to be addressed and accounted for, by Malaysians. These external factors in the long run will also influence the widespread use of BiPV technology and local agendas will need to be drawn in the overall planning of the country's development.

Summary

In summary, it can be concluded that most factors favour the introduction of BiPV technology use, at least at the pilot and demonstration stages. Building on confidence and acceptance of the numerous established remote PV power systems in Malaysia, the anticipated success of BiPV applications in rural Malaysia seems inevitable, given the impetus of the national electrification plan. These BiPV installations may be linked to a localised grid with back-up systems. The technology and experience are available. All it seems to need now, is a start.

Its eventual widespread use throughout the country especially in the urban areas may take a longer time, depending on the economic fluctuations and political factors. The major damping factor for its widespread use in the urban areas seems to be the higher initial costs. This is consistent with earlier experiences in other pioneer countries. For Malaysia, in her present economic achievements as a developing nation, this massive economic inertia may not be seen as justifiable on a grand scale in the urban areas yet, but seems ripe for introduction and demonstration applications. This is in relation to the prevailing national plans and budget allocations for electrifying the country. In addition, BiPV technology will not be seen as a very alien technology by policy makers as traditional PV power systems has long been established in more remote areas of the country.

In tandem with economic issues, political factors for Malaysian applications also deserve due consideration as it often serves as an extension of the levels of commitment of Malaysians with regards to sustainable technologies directly, and BiPV technology indirectly. Factors affecting these economic-political issues need to be studied further and better understood to qualify any meaningful projections with regards to BiPV technology proliferation in Malaysia.

10.5 Recommendations for further BiPV-Malaysia research

Based on the findings of the research project, it is recommended that further research be done in the following areas:

1. Set-up of a practical BiPV-SMSB test installation: As a direct consequence of this exploratory simulative study, a practical BiPV-SMSB installation is suggested to be built as a test case. In the first instance, a pilot BiPV-SMSB school that more or less matches the assumptions made in this project would be selected. Since the calculations have been based on the average classroom size, any generic SMSB school is expected to quite nearly meet this criteria. The major requirement may be relating to obtaining permission from all the authorities concerned, with such a "new" technology and its impact on the "views of certain authoritative bodies" due to the system's "generating capability". This pilot installation shall provide practical confidence and shall serve to convince authorities of its practicality, prior to further applications. The standard Malaysian building, M&E regulations and installation procedures shall be adhered to, with advice and supervision from consultants with previous experience; e.g. from the UK or Australia. The proposed pilot installation is best initiated using funding from the R&D sector on energy within the Ministry of Science, Technology and Environment. As it advances, progressive plans for

other stages of installations and related issues shall be studied in more detail. More comprehensive BiPV programmes may then be proposed to the more directly relevant authorities; e.g. Ministry of Education and Ministry of Rural Development.

2. Monitor and analyse such installations: Complete computerised monitoring systems such as those used in this research project are proposed to be installed. With regards to the pilot BiPV-SMSB installation, experiences from the BiPV-WHF installation will serve as a guide and monitoring techniques would be further enhanced: e.g. remote downloading of data through a modem. As more systems are installed, a more comprehensive data-logging and analysing plan shall be designed, drawing from the experiences of other pioneers such as SONNE-Online, FhG-ISE in Germany and PV-Monitor, METEOTEST in Switzerland. Standard logging formats such as the JRC Ispra in Italy shall be adhered to, in conformity with international conventions.

3. Detailed studies on controlling the cell temperature in BiPV-SMSB systems: Drawing on the findings from this research project, it was found that cell and module temperatures have an especially significant influence on the system's performances in Malaysian applications. Especially in relation to the higher ambient temperatures in Malaysia, the practical roof-top integrated PV modules are anticipated to have higher temperatures as described in the relevant Chapters. Thus, emphasis shall be given to better architectural designs of the BiPV in the SMSB design specifically, and the Malaysian built-environment generally. More complex and comprehensive thermal and ventilation model packages for simulating temperatures and air flows for the BiPV designs may be considered.

4. Other BiPV-Malaysian installations: New simulation work may be explored on other buildings in the Malaysian built environment that tend to have large roof areas with relatively low energy demands. A good prospect is the residential house in housing estates.

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Appendices

POWER SYSTEMS INTERNATIONAL LIMITE

CERTIFIED TEST RESULTS

PRODUCT 5.0 kW Photovoltaic-Inverter | FILE REF E94-2499

OUR REF E94-2499 DATE 30.9.94
WORKS REF SERIAL NO SN90418
CUSTOMER REF 72013P

CUSTOMER SOLAPAK LIMITED
UNIT 2, COCK LANE,
HIGH WYCOMBE
BUCKS., HP13 7DE

DESCRIPTION Photovoltaic-inverter

INPUT VOLTS 240Vac - 400Vdc
FREQUENCY
PHASES

OUTPUT VOLTS 230V/3x400V only for grid monitoring
FREQUENCY 50 Hz
PHASES 1/3

CAPACITY .... kVA at 0.8 PF
" 5.0 kW

SOURCE CODE PSI-PV-WR5000
LOCATION/ORIGIN European Union

RECTIFIER

INPUT AC VOLTAGE 1 Phase ☐ 3 Phase ☐ Vn ......
Vn TOLERANCE +/- ...... % CHECKED ☐
INPUT FREQUENCY ...... Hz +/- ...... % CHECKED ☐
INPUT MAX CURRENT 1 Phase......AC 3 Phase......AC ☐
OUTPUT MAX CURRENT ...... Idc CHECKED ☐
OUTPUT VOLTAGE ...... Vdc +/- ...... % CHECKED ☐

PERFORMANCE/STABILITY

Vac (Vn)	Vdc	Idc Amps	RIPPLE Vpp/RMS	LOAD %
+ %				
Vn				0
- %				
+ %				
Vn				25
- %				
+ %				
Vn				50
- %				
+ %				
Vn				75
- %				
+ %				
Vn				100
- %				
+ %				
Vn				110
- %				

BATTERY

NO OF CELLS .... PB ☐ Nicd ☐
FLOAT VOLTS .... per cell
AUT BOOST CHARGE .... V/cell
MAN BOOST CHARGE .... V/cell
CAPACITY .... Ah
MAKE ....

CHARGE VOLTS	FROM	TO	SET
FLOATING			
AUT BOOST			
MAN BOOST			

CURRENT LIMIT SET AT .... A

AMBIENT TEMP ☐ °C TEMP RISE AFTER 8 HOURS ☐ °C

CONT.

A.1 Copy of certified test certificate for SMA PV-WR2325 inverter

INVERTER

INPUT VOLTAGE RANGE FROM 240.. Vdc TO 400. Vdc NOMINAL 300.. Vdc, Max. 450 Vdc Open Ci-rc.

NOMINAL OUTPUT VOLTAGE 230. Vac NOMINAL FREQUENCY .50.. Hz NOMINAL CURRENT 17.... Iac, PHASE

Vdc INPUT	Idc INPUT	kWdc INPUT	Vac OUTPUT			OUTPUT CURRENT (Iac)			kW OUTPUT	HARM DIST %	LOAD %	COS PHI	EFFY %
			R-S	S-T	T-R	R	S	T					
											0		
250	5	1,25	400	400	400	4,97	—	—	1,142		25	1	91,4
"	10	2,5	only for grid		"	10,06	—	—	2,313		50	1	92,5
"	15	3,75	monitoring		"	14,97	—	—	3,443		75	1	91,8
"	20	5	"	"	"	19,9	—	—	4,575		100	1	91,5
"	25	5,5	"	"	"	21,6	—	—	4,961		110	1	90,2
											125		

BURN-IN/LOAD TEST AS RECORDED ABOVE

DATE	1.12.94	1.12.94	1.12.'94	1.12.'94	2.12.'94	2.12.'94	
% LOAD/kVA	0 0	25%	50%	75%	100%	110%	125%
HRS/MINS	30 mins	10 mins	10 mins	10 mins	12 h	30 mins	

PROTECTION

INVERTER STOPS AT : INPUT DC VOLTS | 240 DCV | LOW LIMIT AND AT | 400 DCV | HIGH LIMIT

AND WITH OUTPUT CURRENT LIMIT SET AT | 22 Iac | SHORT CIRCUIT TESTED | YES | ~~NO~~

INVERTER TRANSFERS TO BYPASS IN | — MSec | AND RESETS IN | — MSec

ELECTRONIC PROTECTION FUNCTIONS AT ALL LIMITS STATED | YES | ~~NO~~

VOLTAGE REGULATION

STEADY STATE 0 - 100% LOAD | +/- — % | +/- 50% RATED LOAD | +/- — %

+/- 100% RATED LOAD | +/- — % | REGULATION TIME DOES NOT EXCEED | — MSec

STATIC SWITCH

INVERTER TRANSFERS TO BYPASS LINE AT OUTPUT VOLTAGE | Vac | LOW | Vac | HIGH

TRANSFER TO BYPASS IS BLOCKED WHEN BYPASS LINE VOLTAGE IS | Vac | LOW | Vac | HIGH

TRANSFER TO BYPASS IS BLOCKED WHEN BYPASS FREQUENCY IS | Hz | LOW | Hz | HIGH

TRANSFER TIMES : INVERTER TO BYPASS | MSec | BYPASS TO INVERTER | MSec | CHECKED

RETRANSFER FROM BYPASS LINE TO INVERTER OCCURS BETWEEN VOLTAGE LIMITS

THE STATIC SWITCH TESTS WERE CONDUCTED WITH | FULL | RATED | kVA | kW | LOAD CONNECTED

POWER FREQUENCY TEST MM ....

.... kV x .... s at .... Hz

RFI TEST ..VDE 0871, A..................

INSULATION RESISTANCE MEASUREMENT V

MM ....

OTHER TESTS ....

INSPECTOR ...Greizer............ SIGNATURE ...Greizer......... DATE ..20.12.1994.

A.1 Copy of certified test certificate for SMA PV-WR2325 inverter

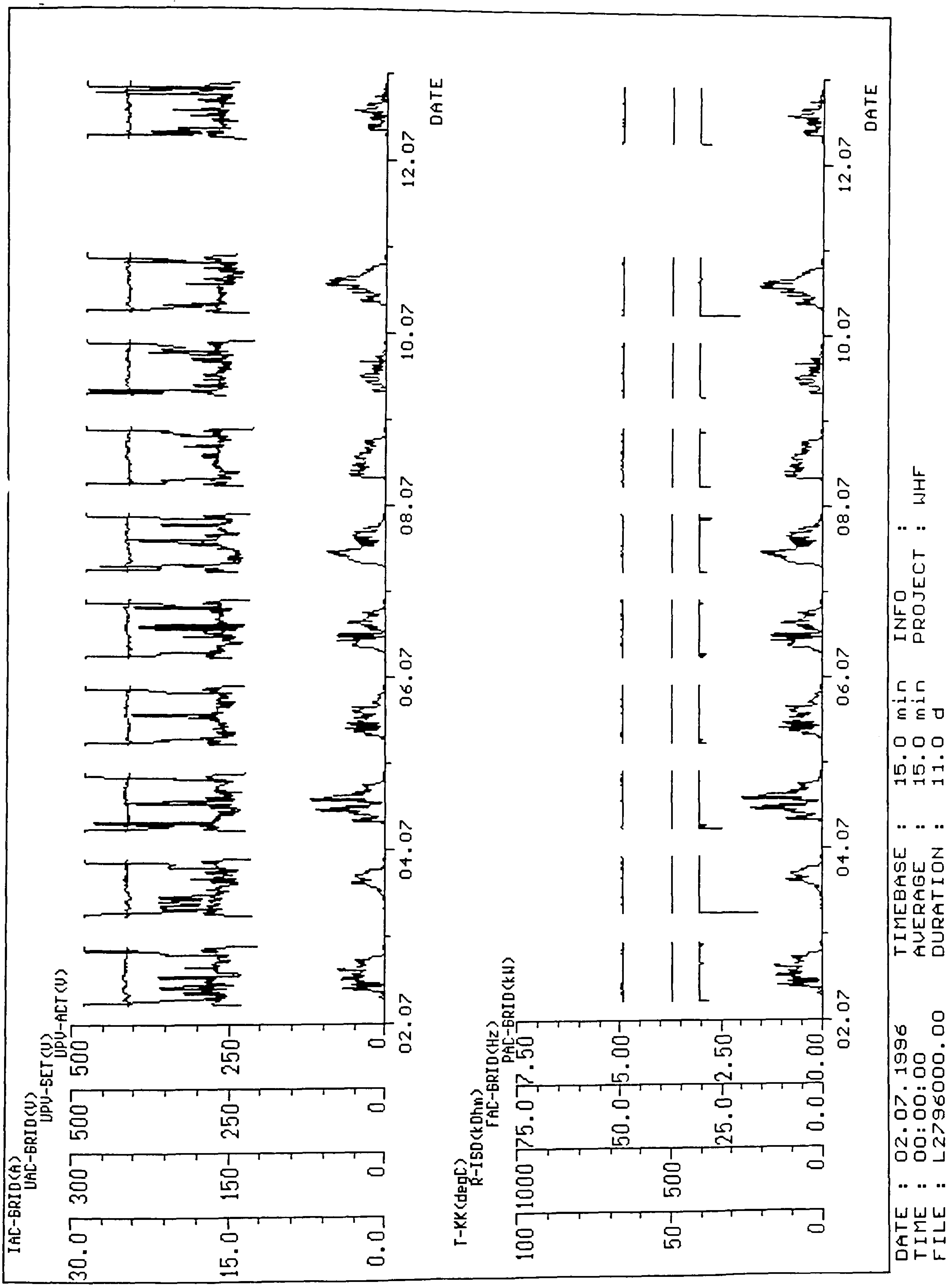
```
S M A - PV WR
File        Online        Events        FAults        Data        Graphic        OPtions

 About
 OS-Shell   :   WR
 Exit       : 0
            : 1
  COM Port  : 1

                    Info

                   PVDATA
                Version 2.6.1
      (C) SMA Regelsysteme GmbH 1993
              Tel.: 0561/9522-0
             All rights reserved
```

About PVDATA

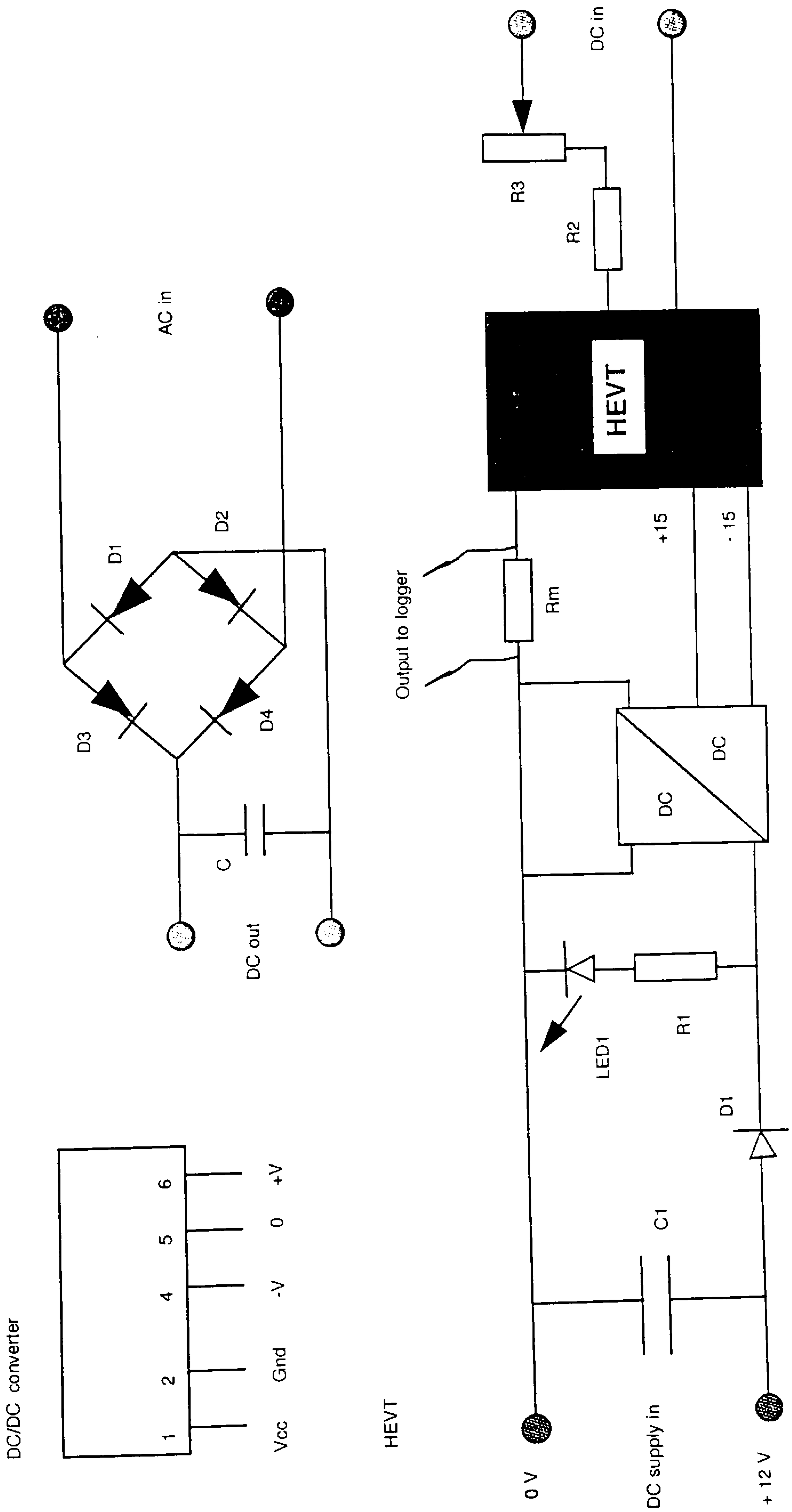
```
S M A   PC - M E S S Y S   2.01
File        Graphics        Options        Tools                Printer

                                              STATE

                                        PROJ  : WHF
                                        FILE  : L1397000.00
                                        DRIVE: C:
                                        PATH  : ..\PVDATA
                                        DEV   : DESKJET EW
                                        DEST.: LPT1
                                        MEM   : 335 kB
                                        EMS   : OFF
```

Tabular data evaluation

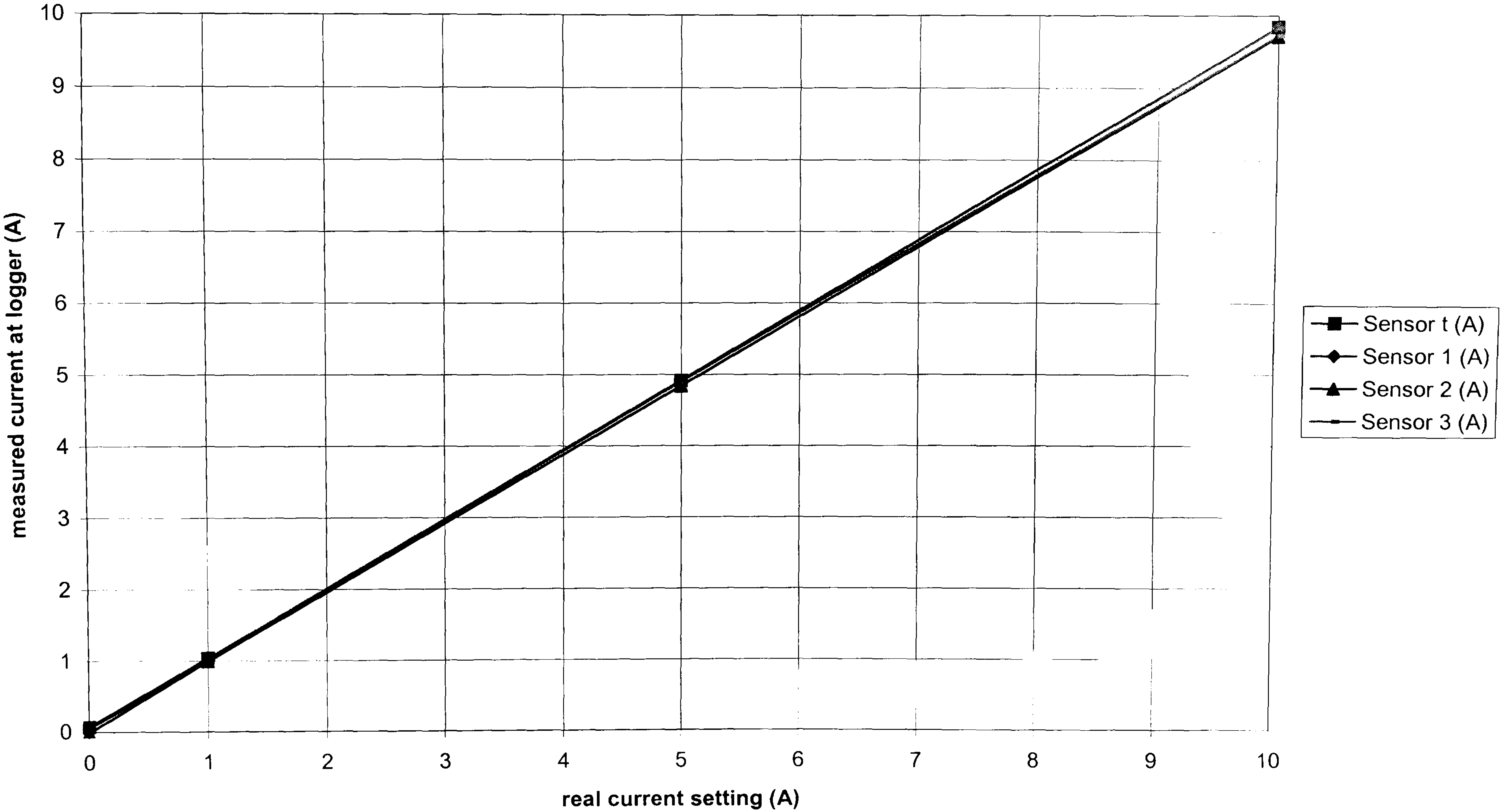
A.2 On-screen PVDATA communication menu and sample output



A.2 On-screen PVDATA communication menu and sample output



A.3 Wiring circuit diagrams for HECT and HEVT



CALIBRA1.XLS

A.3 Scatter plot for HECT DC calibration values vs real current values used at BiPV-WHF installation

HECT-DC calibration

Events of PVWR5000 - Station nr. 2325 - 6/ 8/1996 11:47: 1

Date	Time	Nr.	Event
06/08/96	11:16	7	MPP-Found
06/08/96	11:14	6	MPP-Searching
06/08/96	10:44	7	MPP-Found
06/08/96	10:43	6	MPP-Searching
06/08/96	10:13	7	MPP-Found
06/08/96	10:11	6	MPP-Searching
06/08/96	10:11	4	Automatic MPP-Tracking
06/08/96	10:11	3	Device start-up
06/08/96	10:10	2	Device waiting
06/08/96	10:10	1	Device stopped
06/08/96	10:09	8	Device shut-down on Pac-min
06/08/96	10:09	7	MPP-Found
06/08/96	10:07	6	MPP-Searching
06/08/96	10:07	4	Automatic MPP-Tracking
06/08/96	10:07	3	Device start-up
06/08/96	10:06	2	Device waiting
06/08/96	10:06	1	Device stopped
06/08/96	10:05	8	Device shut-down on Pac-min
06/08/96	09:57	7	MPP-Found
06/08/96	09:55	6	MPP-Searching

Faults of PVWR5000 - Station nr. 2325 - 6/ 8/1996 11:47: 4

Date	Time	Nr.	Type	Fault
06/08/96	08:23	2	1	High grid voltage
06/08/96	08:22	2	1	High grid voltage
06/08/96	08:09	2	1	High grid voltage
06/08/96	07:23	2	1	High grid voltage
06/08/96	07:20	2	1	High grid voltage
06/08/96	07:18	2	1	High grid voltage
06/08/96	07:16	2	1	High grid voltage
06/08/96	07:12	2	1	High grid voltage
06/08/96	07:07	2	1	High grid voltage
05/08/96	19:02	2	1	High grid voltage
05/08/96	18:58	2	1	High grid voltage
05/08/96	18:46	2	1	High grid voltage
05/08/96	18:45	2	1	High grid voltage
05/08/96	18:44	2	1	High grid voltage
05/08/96	18:42	2	1	High grid voltage
05/08/96	18:19	2	1	High grid voltage
05/08/96	13:03	2	1	High grid voltage
05/08/96	12:54	2	1	High grid voltage
05/08/96	12:51	2	1	High grid voltage
05/08/96	12:48	2	1	High grid voltage

A.4 Faults registered in EPROM memory chip of SMA PV-WR2325 inverter

PVSYST 2.1		20/05/98 16h22

Characteristics of a PV module

PV module : **Siemens, M 55 - WHF**

File SIEM55.PAN from 13/02/98 13h41

STC power (manufacturer)	**Pnom**	**55 W**	**Technology**		**Si-mono**
Module dimensions (W x H)		0.436 x 0.981 m²	Rough module area	Sbr	0.43 m²
Number of cells (parallel x series)		1x 36	One cell area	Scell	97.2 cm²

Specifications for the model (manufacturer or measurement data)

Reference conditions: Temperature	Tref	25 °C	Irradiation	Gref	1000 W/m²
Open circuit voltage	Voc	21.7 V	Short circuit current	Isc	3.65 A
Voltage at maximum power point	Vmpp	17.5 V	Current at max. power point	Impp	3.15 A
=> Maximum power	Pmpp	55.0 W	Isc temperature coefficient	μ Isc	2.3 mA/°C

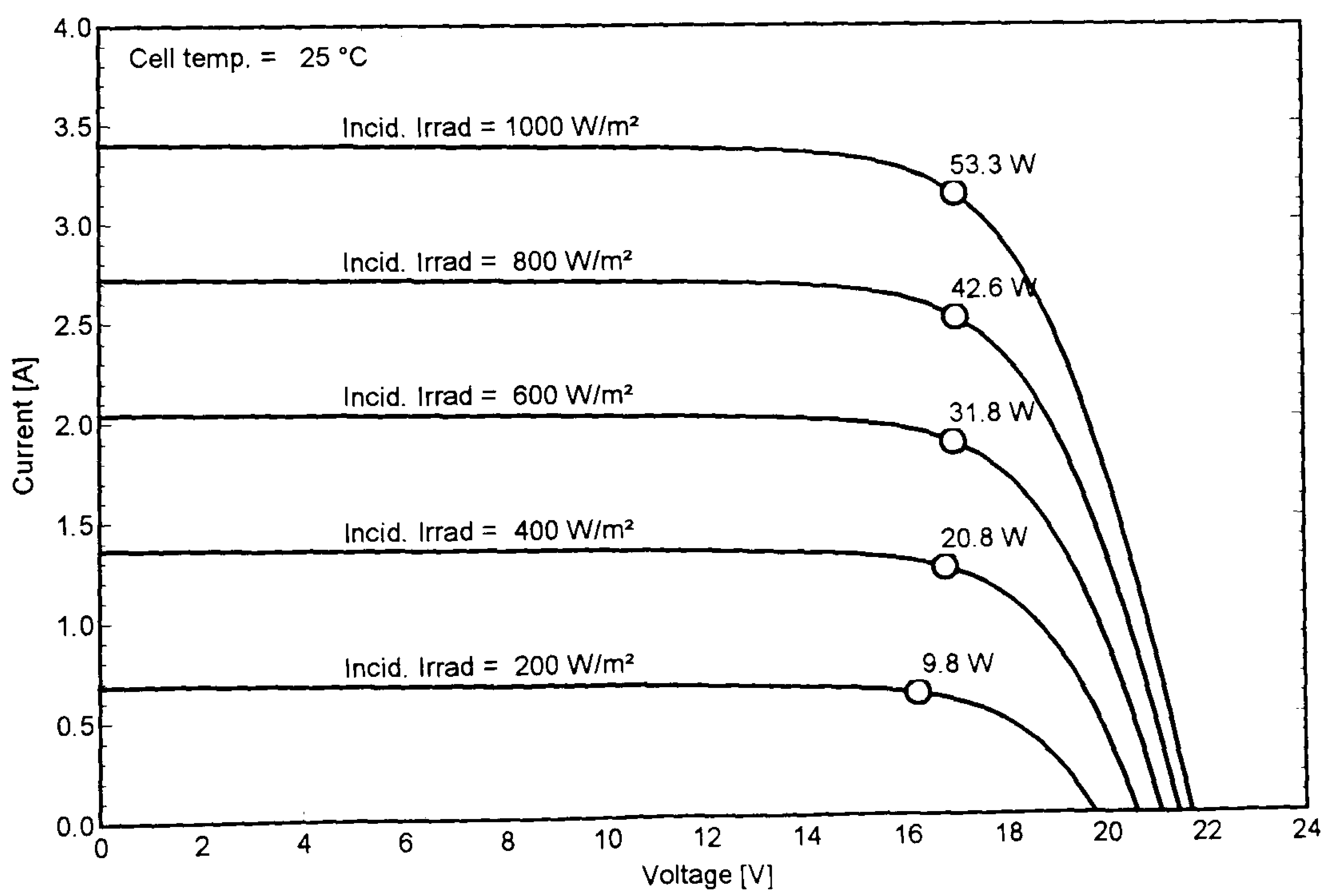
One-diode model parameters

Shunt resistance	Rsh	500 ohm	Satur. current at 20°C	Io	31 nA
Series resistance	Rs	0.50 ohm	Voc temperature coefficient	μ Voc	-73 mV/°C
			Diode quality factor	Gamma	1.27

Special parameters for use in behaviour of PV arrays under partial shadings or mismatch)

Reverse characreristice (darkness)	Arev	3.20 mA/V²	(Quadratic factor per cell)		
Nb of by-pass diodes by module		1	By-pass diode reverse voltage	Vrev	-0.7 V

PV module : Siemens, M 55 - WHF



A.5 Extract of built-in characteristic of Siemens M55 PV module in PVSYST 2.0

PVSYST 2.1		20/05/98 16h14

Characteristics of a PV module

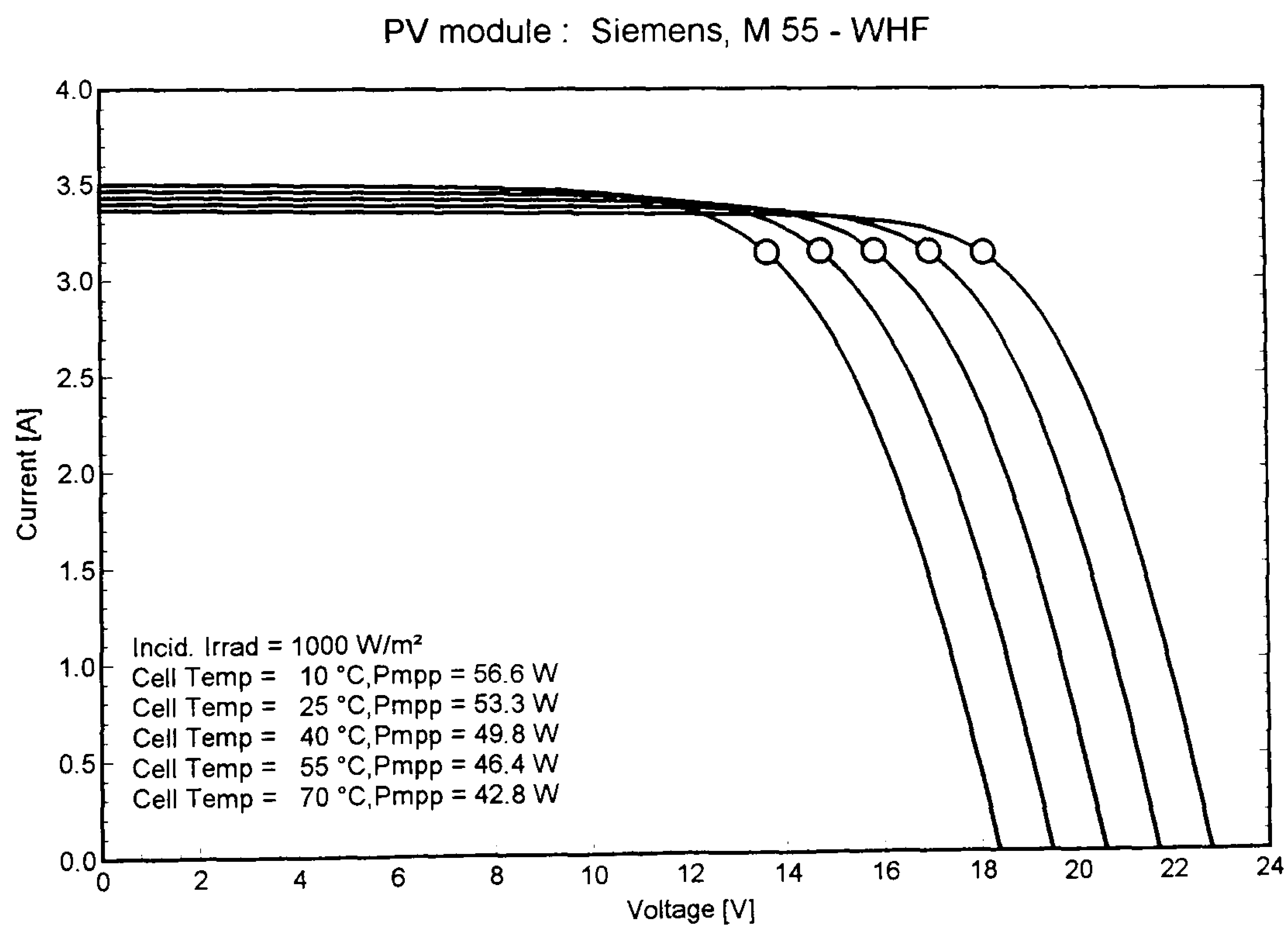
PV module : **Siemens, M 55 - WHF**

File SIEM55.PAN from 13/02/98 13h41

STC power (manufacturer)	**Pnom 55 W**	**Technology**		**Si-mono**
Module dimensions (W x H)	0.436 x 0.981 m²	Rough module area	Sbr	0.43 m²
Number of cells (parallel x series)	1x 36	One cell area	Scell	97.2 cm²

Model results for standard conditions (STC : T=25°C, G=1000 W/m², AM=1.5)

Voltage at the maximum power po	Vmpp	17.0 V	Current at max. power point	Impp	3.13 A
Maximum power	Pmpp	53.3 W	Temper. coefficient	μ Pmpp	-0.43 %/°C
Efficiency (/ module area)	Mod. eff.	12.4 %	Fill Factor	FF	0.722
Efficiency (/ cell area)	Cell eff.	15.2 %			



A.5 Extract of built-in characteristic of Siemens M55 PV module in PVSYST 2.0

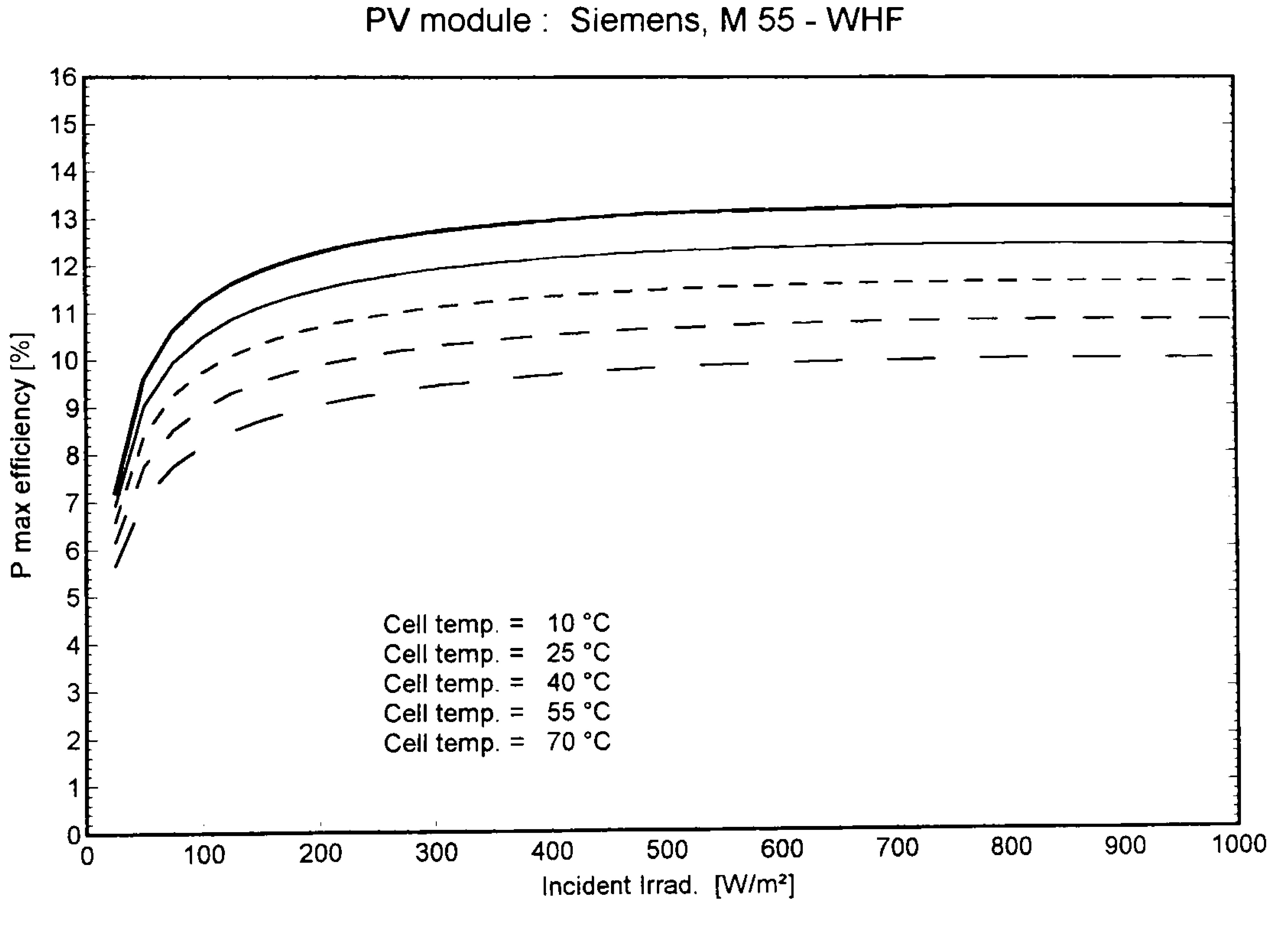
PVSYST 2.1		20/05/98 16h19

Characteristics of a PV module

PV module : **Siemens, M 55 - WHF**

File SIEM55.PAN from 13/02/98 13h41

STC power (manufacturer)	**Pnom 55 W**	**Technology**	**Si-mono**
Module dimensions (W x H)	0.436 x 0.981 m²	Rough module area	Sbr 0.43 m²
Number of cells (parallel x series)	1x 36	One cell area	Scell 97.2 cm²



A.5 Extract of built-in characteristic of Siemens M55 PV module in PVSYST 2.0

PVSYST 2.1		20/05/98 16h26

Characteristics of a PV module

PV module : **Siemens, M 55 - WHF**

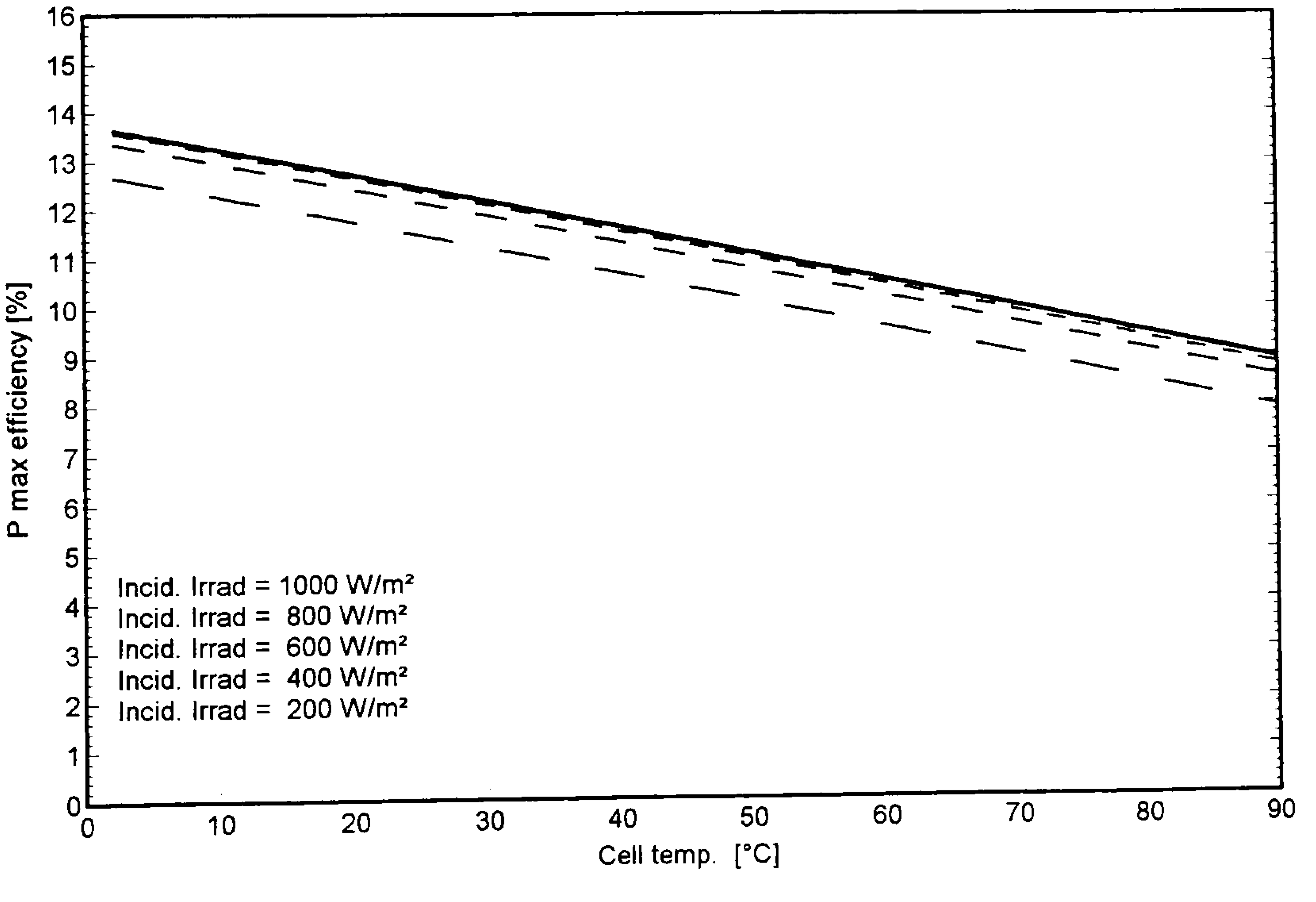
File SIEM55.PAN from 13/02/98 13h41

STC power (manufacturer)	**Pnom**	**55 W**	**Technology**		**Si-mono**
Module dimensions (W x H)		0.436 x 0.981 m²	Rough module area	Sbr	0.43 m²
Number of cells (parallel x series)		1x 36	One cell area	Scell	97.2 cm²

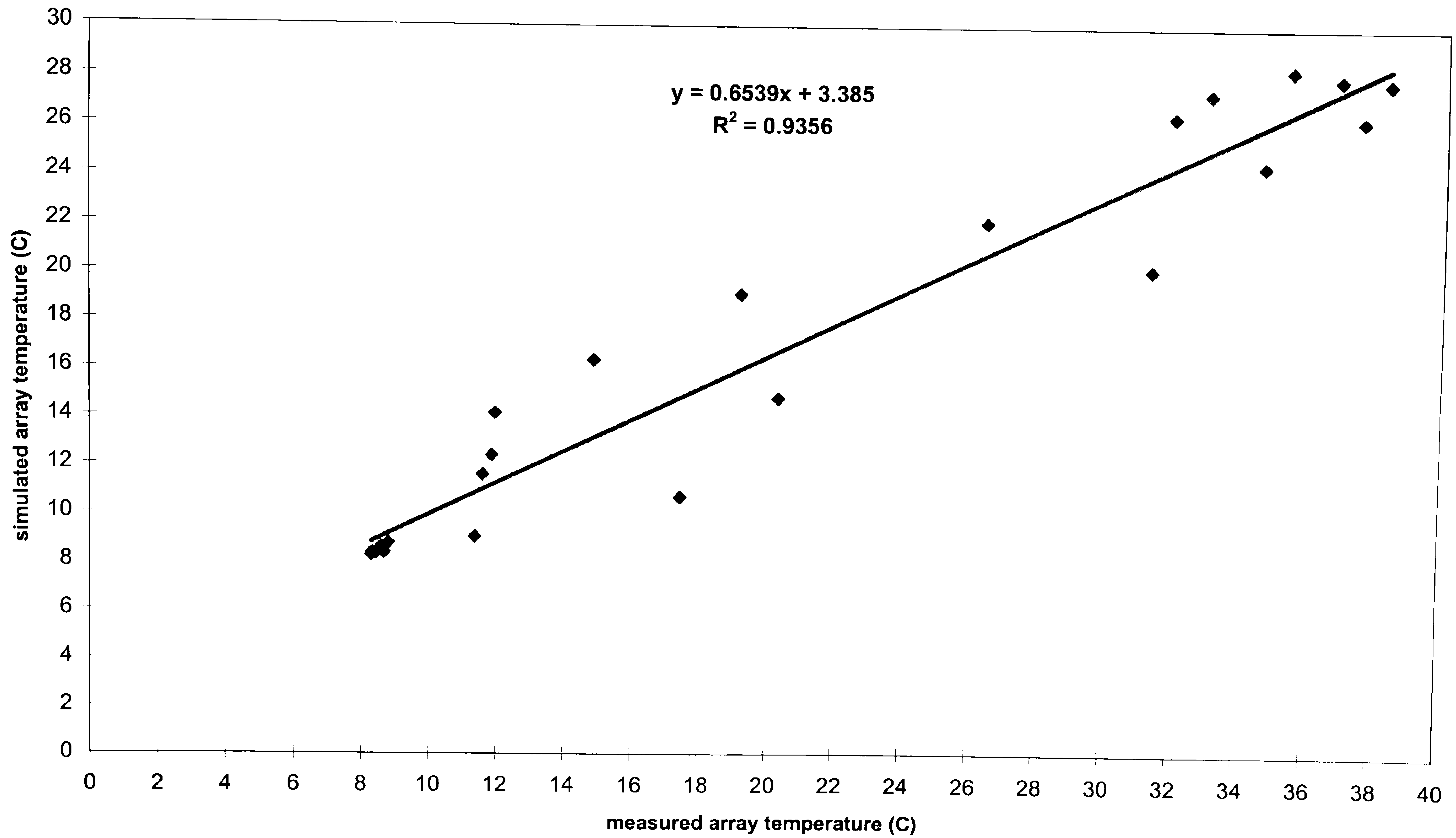
Model results for standard conditions (STC : T=25°C, G=1000 W/m², AM=1.5)

Voltage at the maximum power po	Vmpp	17.0 V	Current at max. power point	Impp	3.13 A
Maximum power	Pmpp	53.3 W	Temper. coefficient	μ Pmpp	-0.43 %/°C
Efficiency (/ module area)	Mod. eff.	12.4 %	Fill Factor	FF	0.722
Efficiency (/ cell area)	Cell eff.	15.2 %			

PV module : Siemens, M 55 - WHF



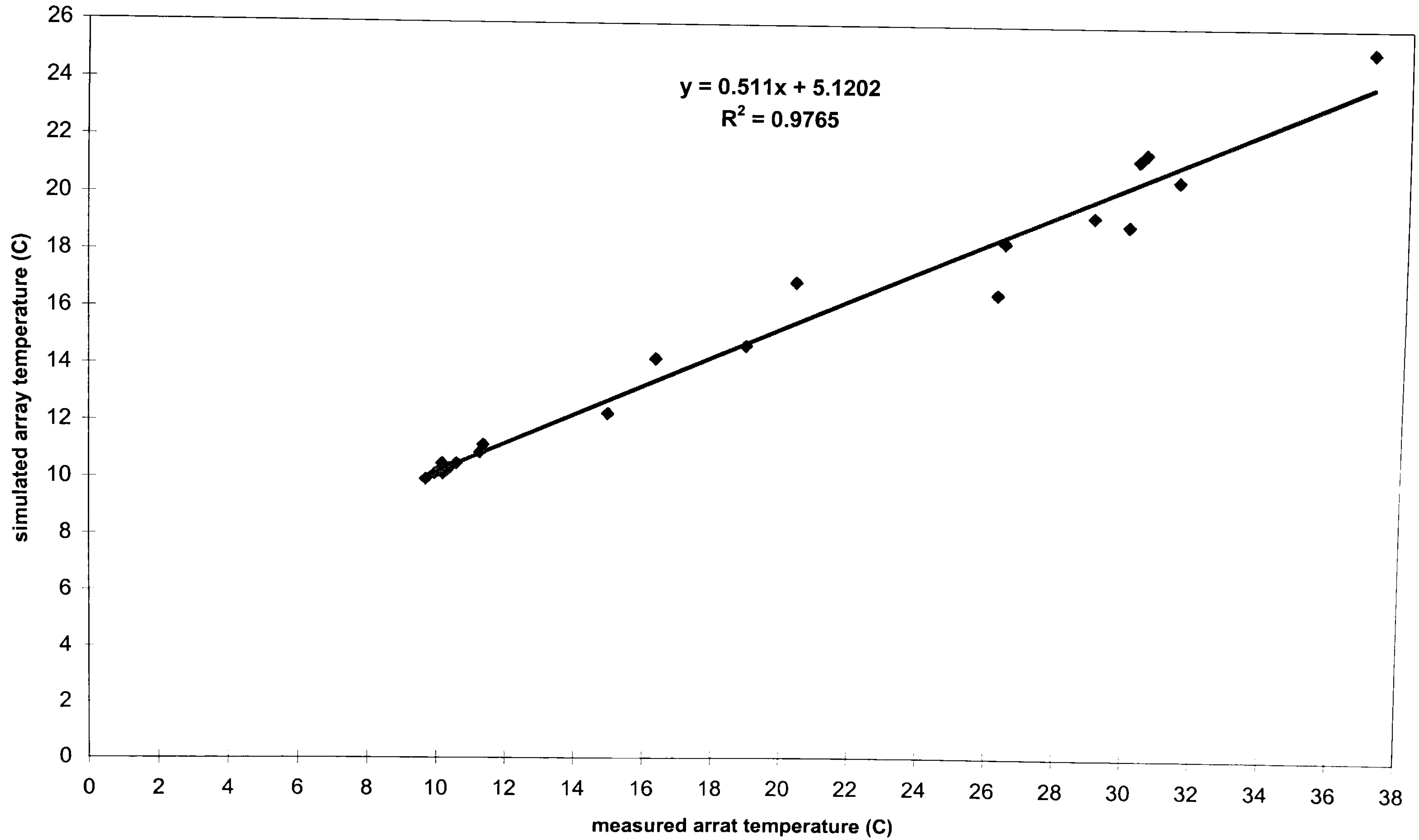
A.5 Extract of built-in characteristic of Siemens M55 PV module in PVSYST 2.0



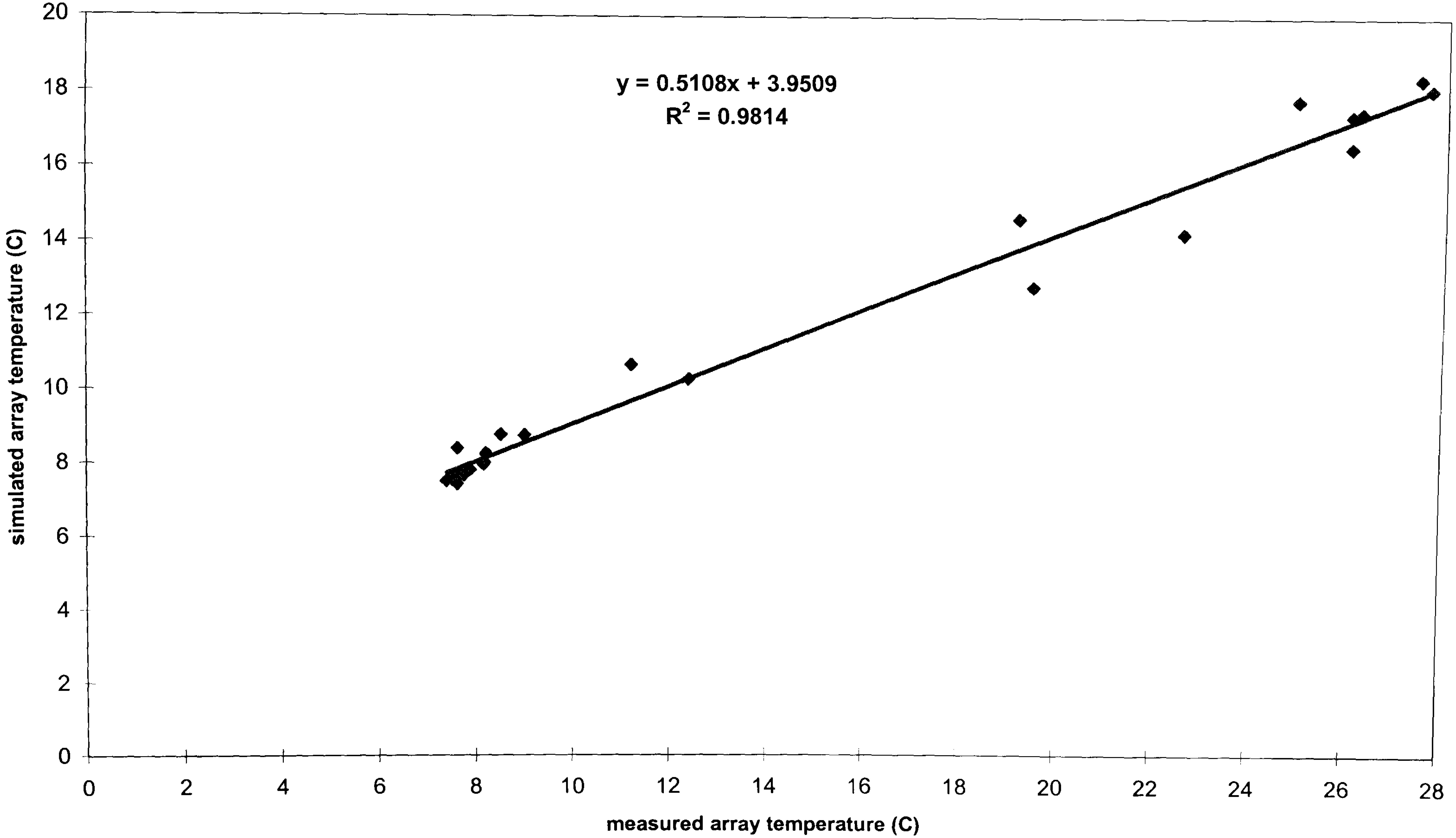
H96-07AV.XLS

A.6.1 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF for July 1996

c-scatter-T



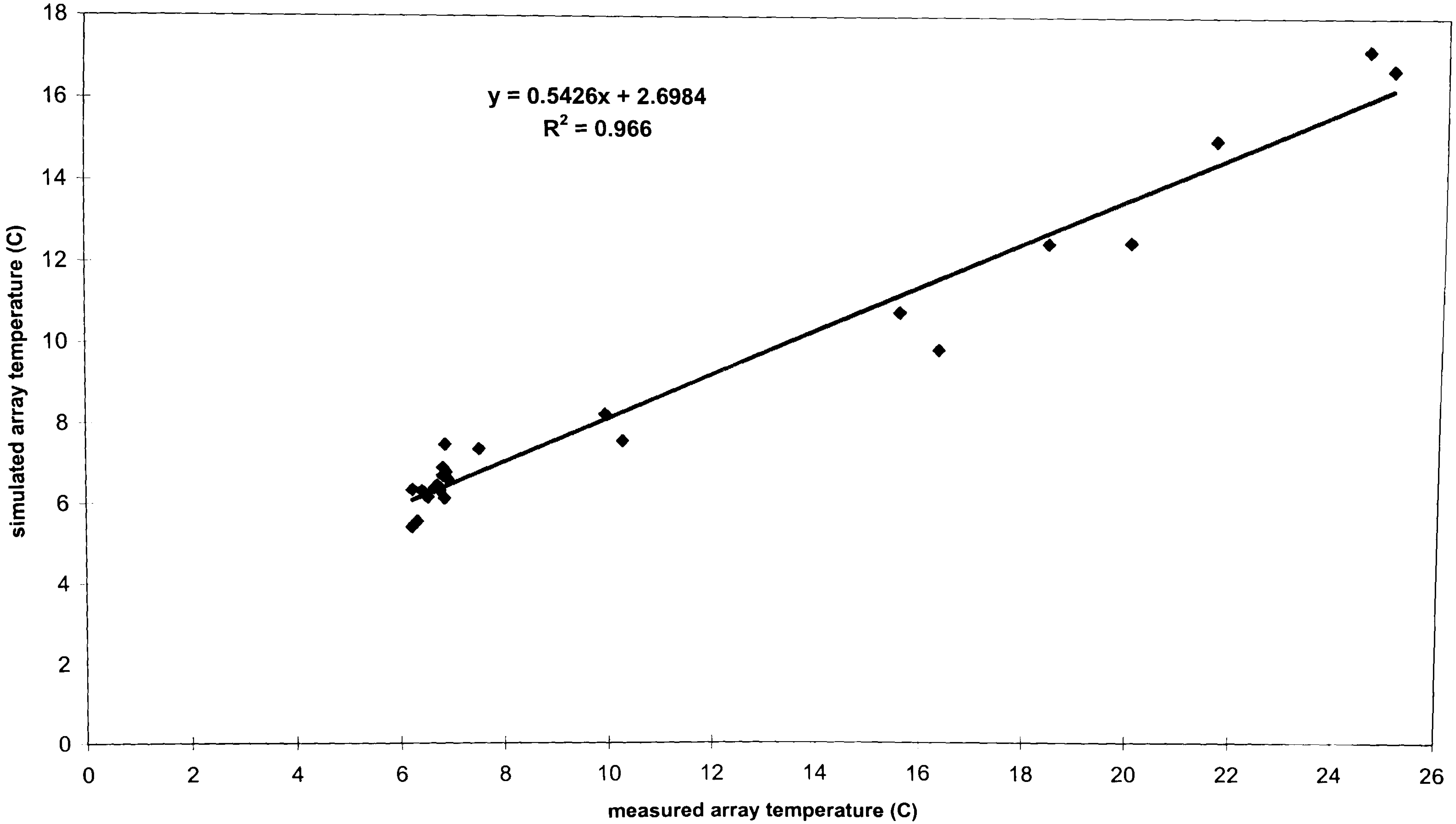
H96-08AV.XLS A.6.2 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF for August 1996 c-scatter-T



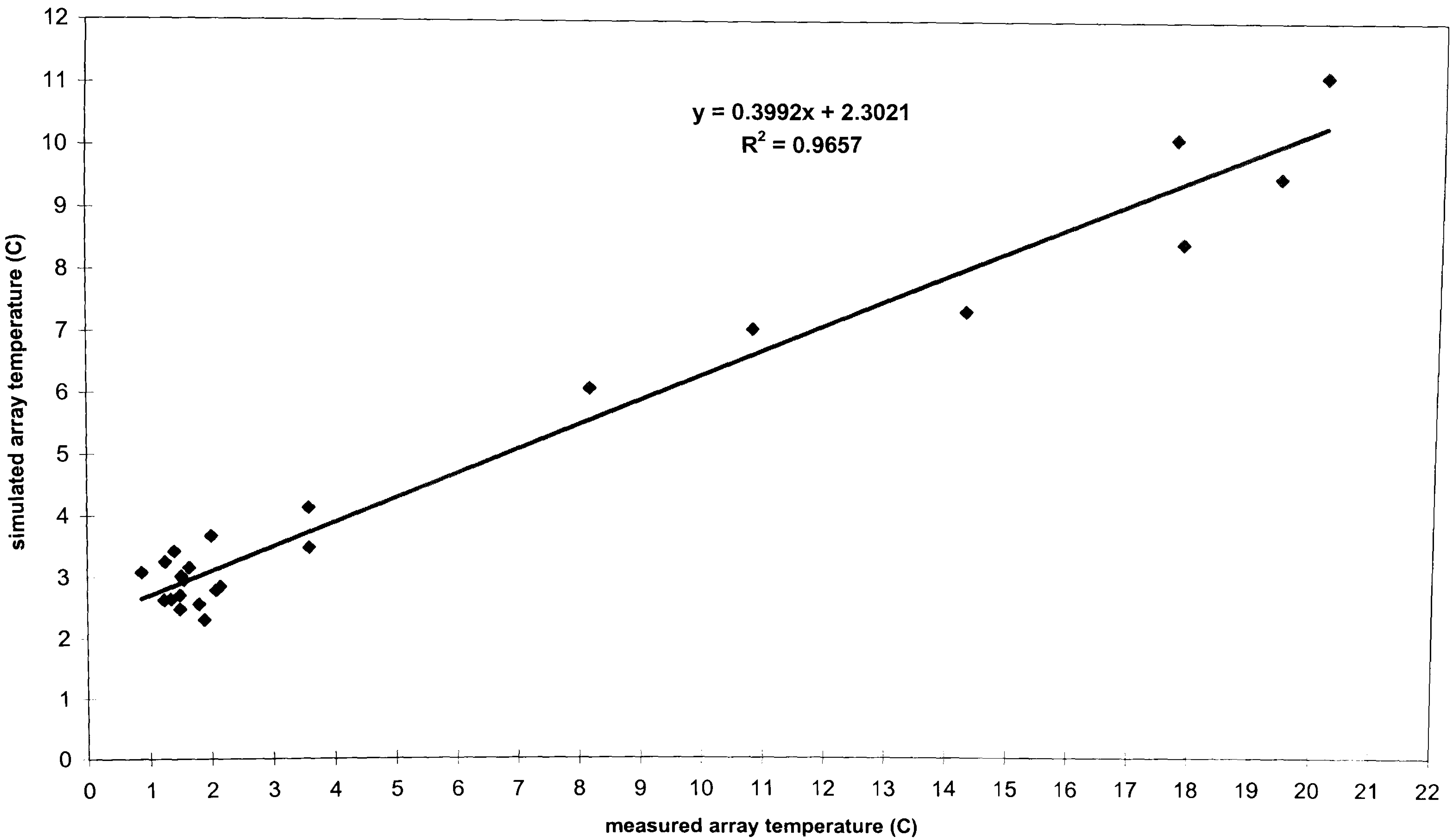
H96-09AV.XLS

A.6.3 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF for September 1996

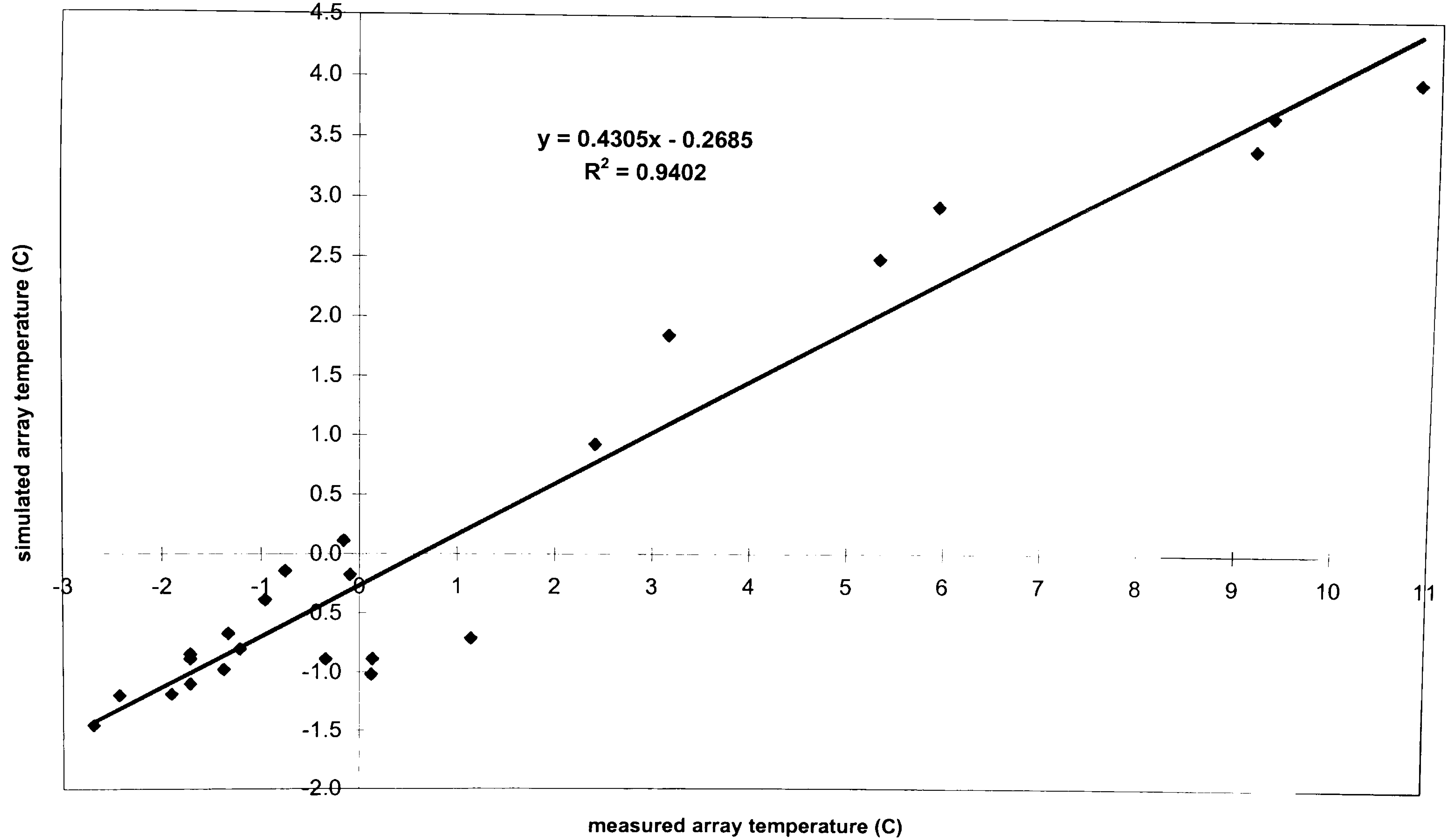
c-scatter-T



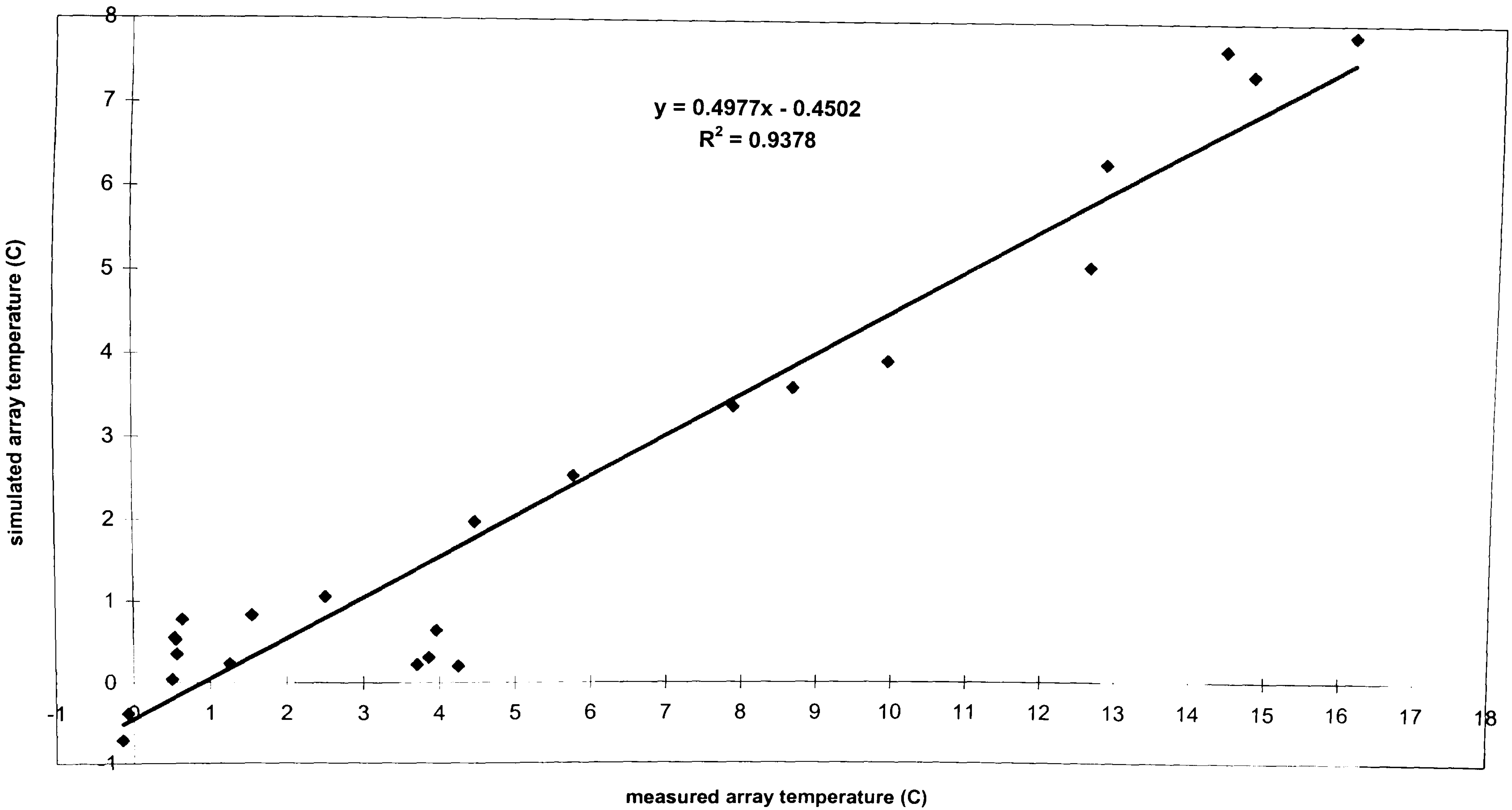
H96-10AV.XLS A.6.4 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF installation for October 1996 c-scatter-T



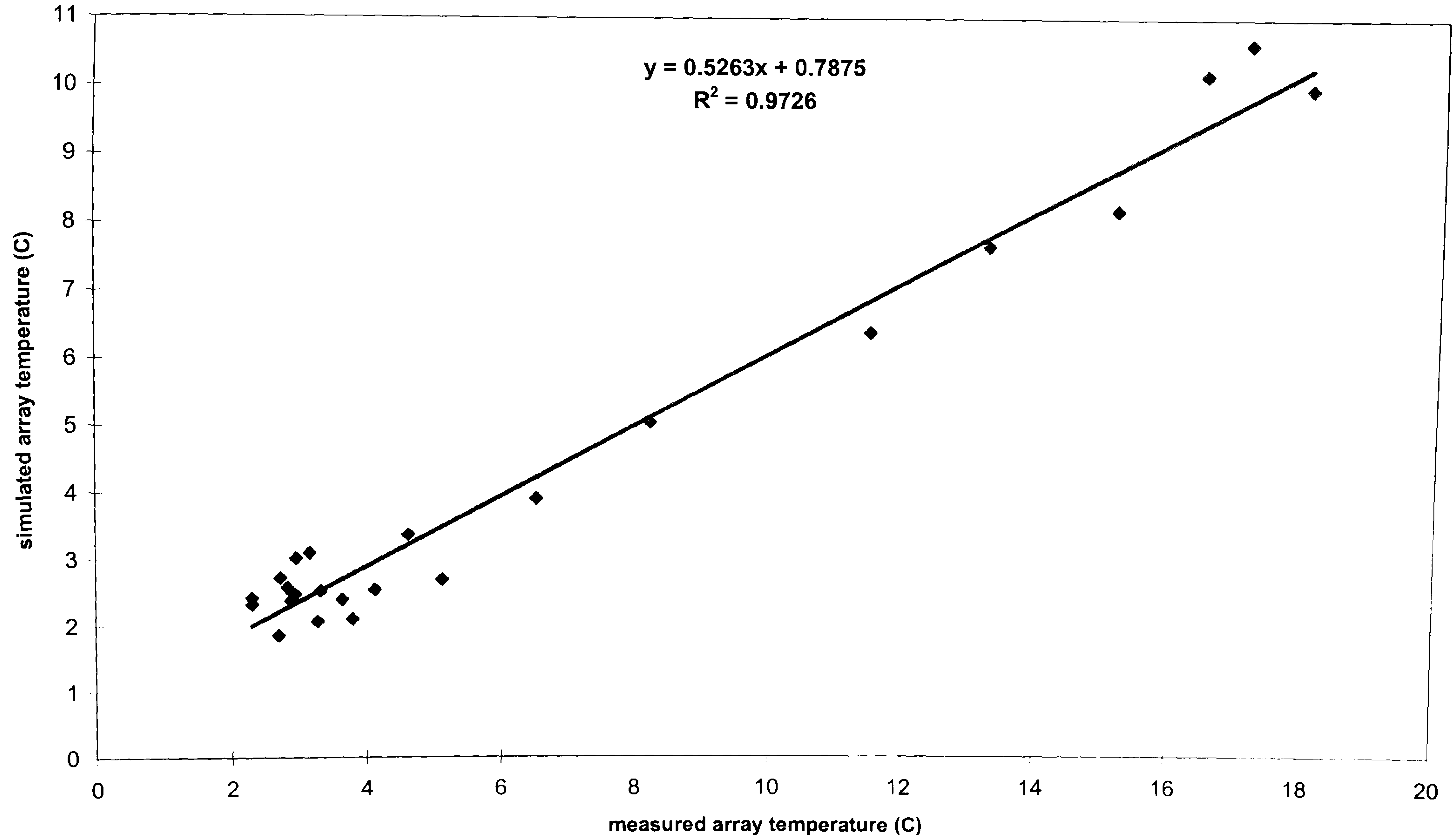
H96-11AV.XLS A.6.5 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF installation for November 1996 c-scatter-T



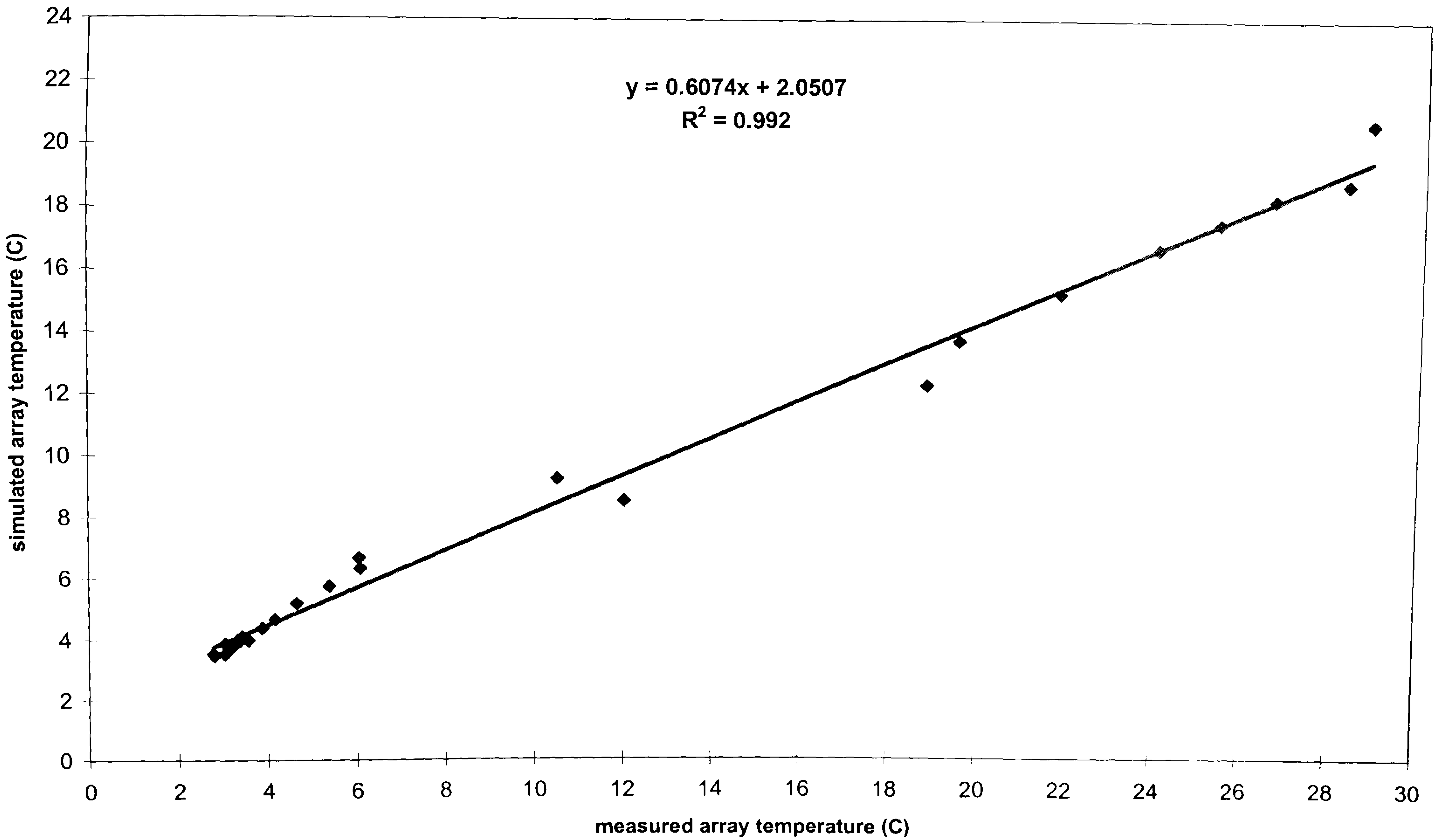
H96-12AV.XLS A.6.6 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF for December 1996 c-scatter-T



H97-01AV.XLS A.6.7 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF installation for January 1997 c-scatter-T



H97-02AV.XLS A.6.8 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF for February 1997 c-scatter-T



H97-03AV.XLS A.6.9 Scatter plot for simulated array temperature vs measured array temperature at BiPV-WHF installation for March 1997 c-scatter-T

PVSYST 2.1		20/05/98 16h34

Near shading situation

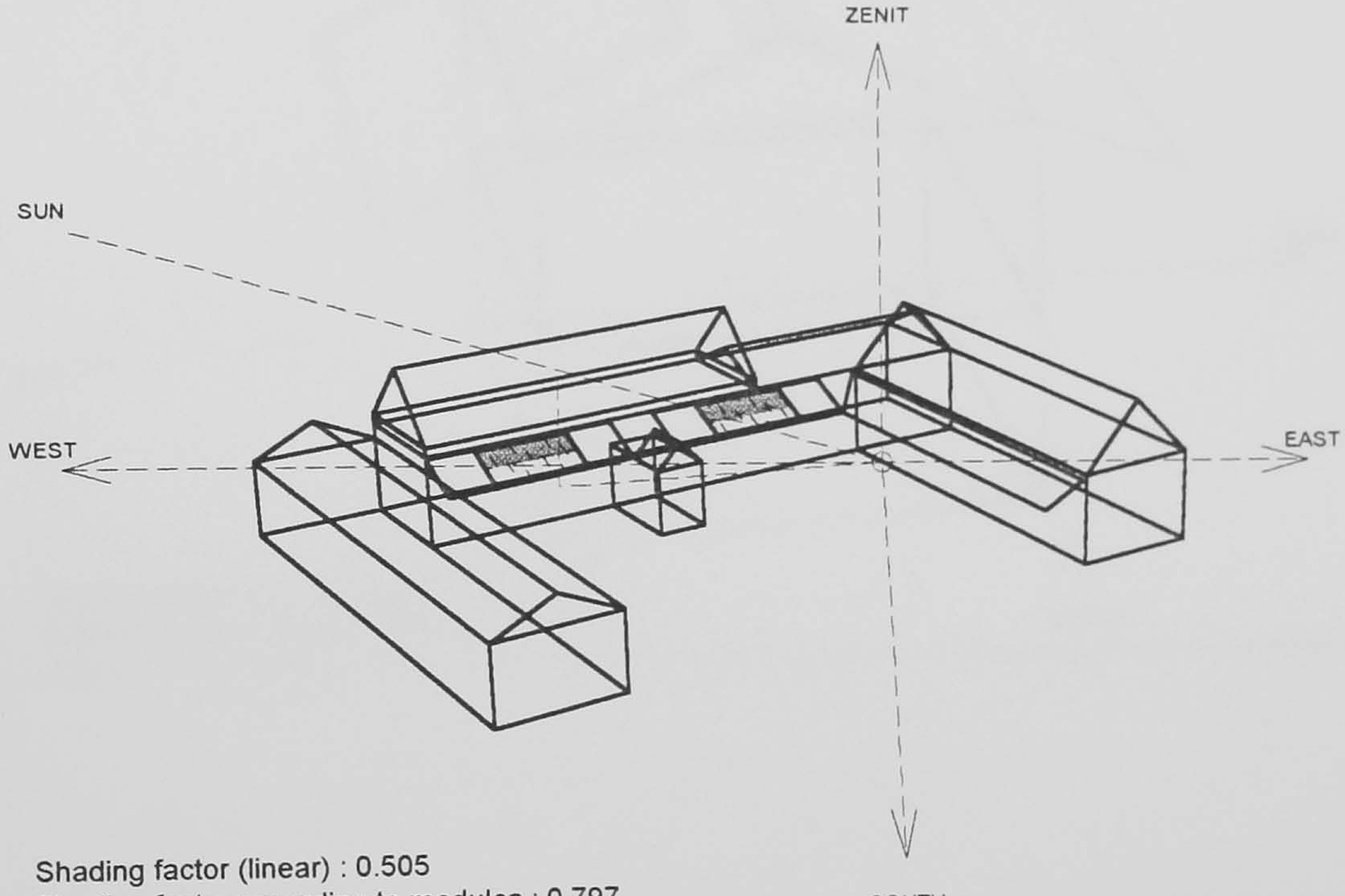
Project : 97-03-B2

Near shadings : **B2**

File B2.OM1 from 24/02/98 12h28

Defined active areas (fields) :	PV2, PV3	Area	16.0 m²
Shading obstacles	ROOF1 ROOF2 ROOF3 ROOF4 BASE2 BLOCK1 BLOCK2 BLOCK3 BLOCK4 ROOF5 ELEVATED BLOCK1		
Collector field orientation	Tilt 25 °	Azimuth	-33 °

Shadings for a given sun position **Height** 20 ° **Azimuth** 79 °



Shading factor (linear) : 0.505
Shading factor according to modules : 0.797

A.7 A 3-D geometric representation of the BiPV-WHF installation in PVSYST 2.0

PVSYST 2.1		20/05/98 16h39

Near shading situation

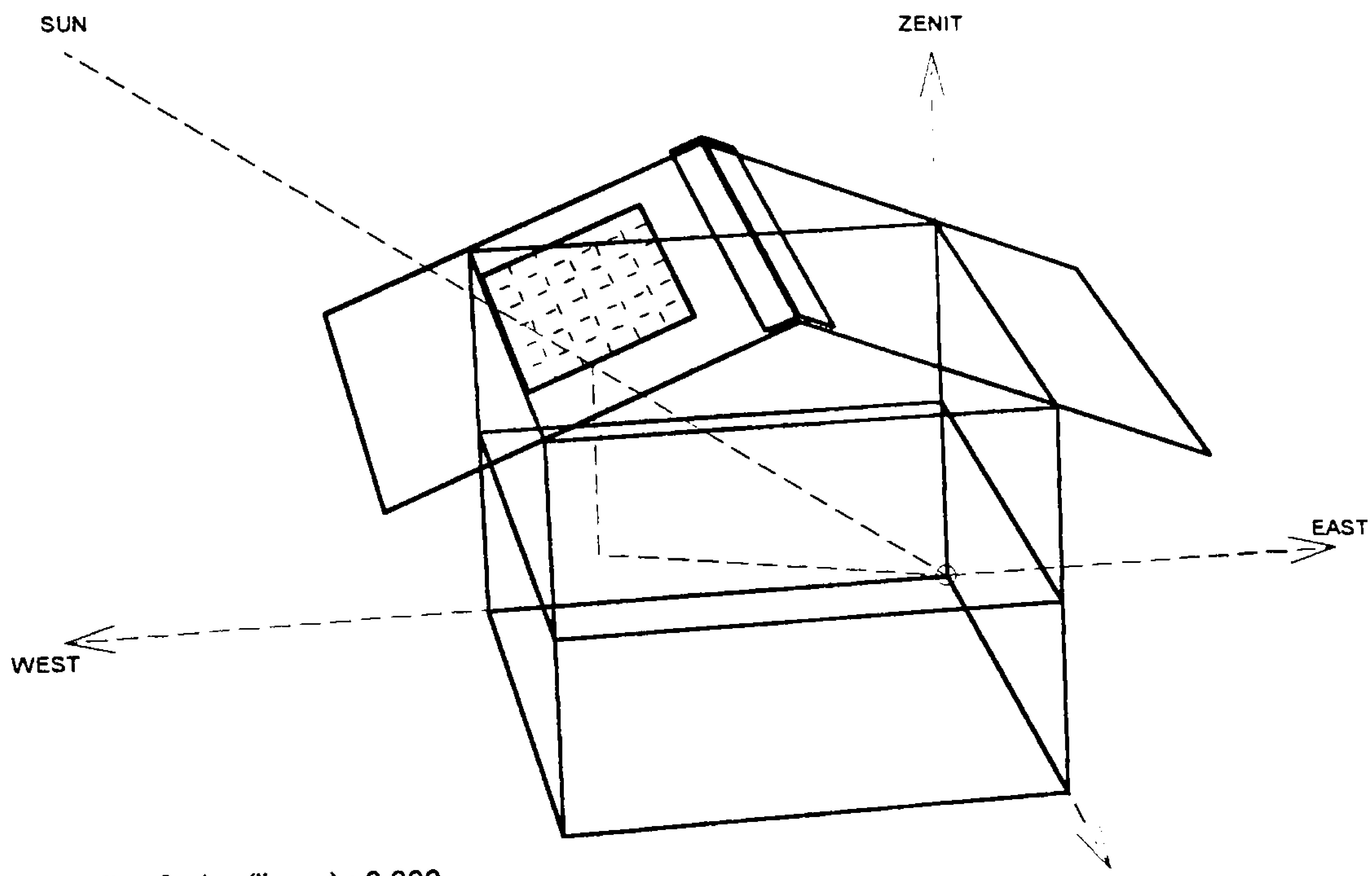
Project : RW5

Near shadings : **RW5**

File RW5.OM1 from 18/03/98 13h20

Defined active areas (fields) :	array1		Area	14.7 m²
Shading obstacles	roof1			
	floor1			
	floor2			
	crest1			
Collector field orientation		Tilt 22 °	Azimuth	90 °

Shadings for a given sun position **Height** 29 ° **Azimuth** 111 °



Shading factor (linear) : 0.000
Shading factor according to modules : 0.000

A.8 A 3-D geometric representation of the BiPV-SMSB design in PVSYST 2.0